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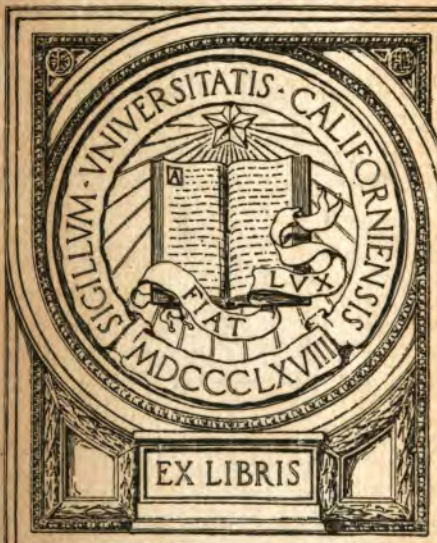

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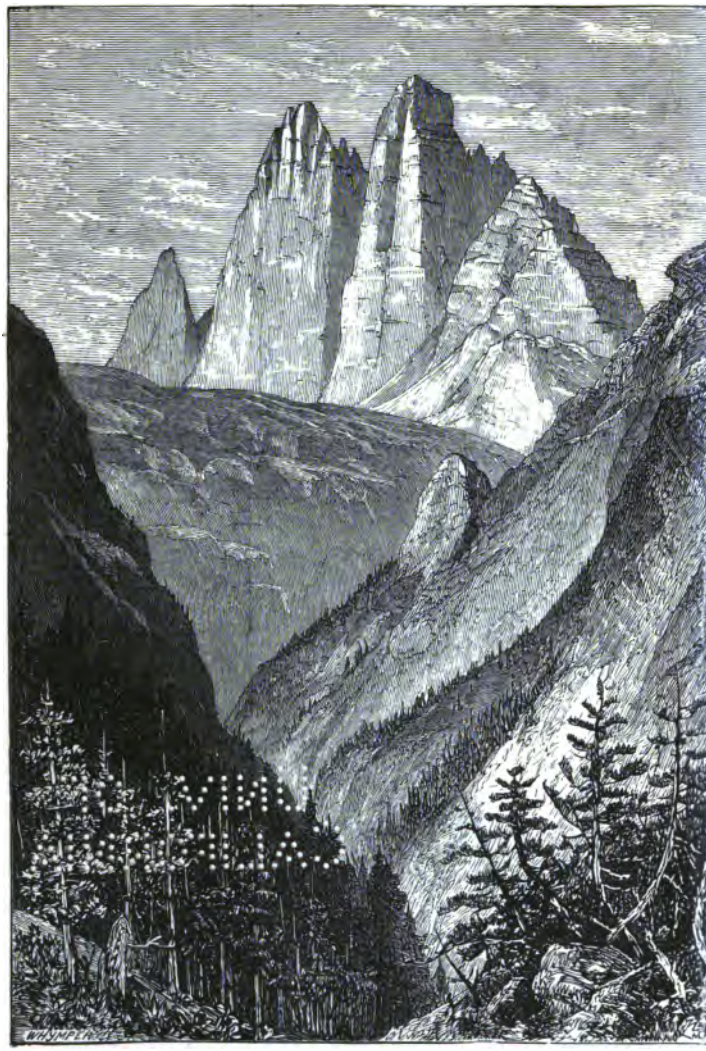

VIEW OF THE DREI ZINNEN (DOLOMITE PEAKS) FROM NEAR LANDRO ;
Showing the forms developed by the weathering of vertical joints.

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THE STUDENT'S HANDBOOK

OF

PHYSICAL GEOLOGY:

BY

A. J. JUKES-BROWNE, B.A., F.G.S.,

OF THE GEOLOGICAL SURVEY OF ENGLAND AND WALES.

With numerous Diagrams and Illustrations.

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PREFACE.

ANOTHER treatise on Geology designed for the use of students may seem uncalled for when such text-books as those of Dr. A. Geikie and Prof. A. H. Green are already in the field; but there does appear to be room for a book of more modest pretensions arranged on a different plan, and issued at a more moderate price,—one with which every individual of a class could provide himself, and upon which the teacher could build up a superstructure of further geological knowledge. Jukes' "Students' Manual," which has been allowed to fall out of circulation, was a book which could be so used, though even that included too much in one volume.

The aim of the present work is to supply the want above expressed; the publishers are fortunately able to secure its issue at a moderate price; and though most of this volume has been written during leisure hours in the country, I have spared no pains to make it a reliable handbook for those branches of the subject which it embraces. In so doing I have received much assistance from my valued friends Prof. T. G. Bonney and the Rev. Osmond Fisher, whose kindness on this and other occasions I have great pleasure in acknowledging.

Prof. Bonney I have to thank not only for many hints and corrections while the work was passing through the press, but also for a valuable contribution in the shape of

an entire chapter on Igneous Rocks, in which the student will find a concise account and classification of these rocks by an author who has made them his special subject of study.

To Mr. Fisher I am also indebted for his kindness in reading over most of the proof sheets, and for many useful suggestions, especially in those portions which refer to the "Physics of the Earth's Crust."

A text-book of geology must necessarily be chiefly occupied in presenting known facts and phenomena, and in describing suitable instances or illustrations of them, but its value for educational purposes must greatly depend upon its plan or system of arrangement, and upon the manner in which its contents are presented to the reader. The general arrangement in this volume is that which has always seemed to me the most natural and the best fitted for the gradual development of the subject. Dry details respecting minerals and rocks are apt to discourage the young student if he is obliged to master them before coming to the descriptive branches of geology.

The arrangement of the matter in each chapter has also been considered, for unless the writer or lecturer forms for himself a clear idea of what he is going to say on each separate subject, he cannot hope to make it clear to his readers or hearers.

Physiographical Geology now takes rank as a primary division of the subject, and its natural place in a text-book seems to be immediately after the sections on Dynamical and Structural Geology. I agree with Mr. G. K. Gilbert of the U. S. Geological Survey, who says, "starting from geological agencies as data, we may proceed in one direction to the development of geological history, or in another to the explanation of terrestrial scenery and topography, and if the development of the earth's history is the peculiar

theme of geology, it follows that the explanation of topography or physiographical geology is of the nature of an incidental result,—a sort of corollary to dynamical geology."

This volume includes only the three branches of the subject mentioned above, those of Palæontological and Historical Geology being left to form another volume.

Most of the diagrams have been drawn by myself, but many views and sketches have been taken from Dr. Mantell's works, a few from Richardson's "Geology," and some from Prof. Bonney's "Alpine Regions," by permission of the author and publishers.

In conclusion, I need only add that I shall feel grateful for any criticisms or suggestions that may lead to the improvement of the work, should it be fortunate enough to reach a second edition.

A. J. JUKES-BROWNE.

Jan. 6, 1884.

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ERRATA.

Page 5, line 35, *for* Physical *read* Dynamical.
Page 7, Part I. should have been headed "Dynamical Geology."
Page 192, line 24, *for* navigable *read* habitable.
Page 215, *omit* the two top lines.
Page 313, line 10, *after* "Current" *insert* Mark.
Page 317, line 6, *for* Cause *read* Origin.

INTRODUCTION.

DEFINITIONS are never easy, and it is especially difficult to frame an accurate definition of Geology, because it is not easy to limit the scope of its application. Two different definitions of the science may indeed be given; one describing it in a broad and comprehensive sense, the other dealing only with its more special and restricted meaning.

Regarded from the wider point of view, Geology is not so much one separate science as the application of all the physical sciences to the examination and elucidation of the structure of the earth. Mr. Jukes has well observed[1] "that we might without impropriety regard all the physical sciences as included under two great heads, namely, astronomy and geology; the one comprehending all those sciences which teach us the constitution, the motions, the relative places, and the mutual actions of the astra, or heavenly bodies; while the other would include all the sciences which deal with the phenomena presented by the one astrum on which we live, and investigate the nature and distribution both of the inorganic matter of the globe, and of the living beings which inhabit it."

The truth of this large and comprehensive view of geology is shown by the very fact of its late appearance in the world of science. The crude ideas regarding the structure and history of the earth, and the nature of fossils which were prevalent in the seventeenth and eighteenth centuries, cannot be dignified by the name of geology.

[1] "Student's Manual of Geology," p. 1.

The *Geognosy*, taught by Werner in the latter part of the eighteenth century, was little more than a special branch of mineralogy; and Desmarest, though an opponent of Werner's views regarding the origin of rocks, treated of geology under the head of physical geography.

It was not, indeed, until much progress had been made in all the physical sciences that geology could possess any solid foundation or any real scientific status. It was not until chemists were able to explain the true nature of the mineral substances which enter into the composition of rocks; until geographers had explored the surface of the earth, and natural philosophers had described the phenomena of volcanoes and earthquakes, rivers and glaciers, tides and currents; until biologists had described and classified the greater number of existing animals and plants —it was not until all these essential data had been collected and studied that the geologist could realize the processes and operations by which rocks were formed, or could utilize his discoveries of the fossil organisms which they enclose.

This necessary knowledge was not possessed by anyone before the beginning of the present century, and, consequently, before this era there was no true science of geology. Hutton's knowledge of chemistry and mineralogy was considerable, and his powers of observation and generalization were truly remarkable, but his lack of information in respect to other sciences necessarily caused his "Theory of the Earth" to be a very imperfect view. It was not till 1790, when William Smith established the two great principles which have caused him to be known as the father of the science, viz., the superposition of stratified rocks, and the identification of strata by their fossil contents, that the foundations of geology were laid; ever since that time materials have been rapidly accumulating for the construction of a true outline of the history of the earth and its inhabitants.

It does not follow from what has just been said that every individual geologist must possess a great and accurate knowledge of the whole circle of physical sciences; it is only necessary that this knowledge should exist, and be readily accessible, so that the geologist can combine the results obtained by other sciences with his own special

observations, and apply them to the solution of the many difficult problems which arise in the course of his researches.

Here the reader may well ask, what are the special observations which the geologist makes, and what is it which he regards as his special business? If the wide scope already indicated be properly given to geology, and if it claims assistance from every other science which treats of anything belonging to the earth; what is it which the geologist teaches to the students of these other sciences in return for the knowledge communicated to him?

The answer to these questions will show that geology has a more limited and applied meaning, which may be defined as follows. Geology in this sense is the application of the knowledge gained by the study of the existing state of things to the elucidation of the past history of the earth. The geologist takes the information gained by others regarding the operations that are now in action on the surface of the globe, and uses this knowledge to explain the results of the operations which have taken place in the past. In this way he is able to explain the manner in which the various rocks have been formed, and the processes by which they have acquired their distinctive characters and their relative positions.

The constitution of the crust of the earth, and the history of its formation, are thus the special objects of his study and research, and, as Mr. Jukes observes, the collection and co-ordination of the facts on which this history is founded is the proper and peculiar business of the geologist: "the ditch, the cutting, the quarry, the mine, the cliff, the gully, the river-bank, and the mountain-side, are his *subjects*, which he has to examine and dissect." From the indications observed in all natural and artificial excavations, he must make out the internal structure or solid geometry of every district, and note all the facts which will enable him to explain the geological history of each natural province or area, until all the accessible portions of the earth's crust have been explored and described, and the "record of the rocks" has been read from beginning to end.

A beginner would probably suppose that in order to

pursue the task of investigating the solid structure of the earth, it would only be necessary to become acquainted with the nature and origin of the rocky matters of which it is composed, and that there would be no occasion for studying the forms of animals and plants. The fact is, however, that an acquaintance with organic remains, as they occur in a fossil state, is even more necessary for a geologist than a knowledge of inorganic substances.

The cause of this necessity may be briefly stated as follows. When portions of the earth's crust came to be examined, it was found that the various rocks of which it was composed were arranged in a regular series, the several rock-groups having been formed one after the other during successive periods, each of long duration. Now, the mineral substances produced during any one of this vast succession of ages do not appear to differ essentially from those formed under like circumstances at another time. We cannot, therefore, with any certainty discover the order of time in which the series of rocks was formed, or their original order of superposition, from an examination of their mineral characters only. The animals and plants, however, which lived at any one period of the earth's history were different from those which lived at other periods. There has been a constant succession of living beings on the earth, different races, species, and genera following each other in a regular order, and when that order has once been ascertained it is clear that any rock containing fossil remains can be assigned to its proper place in the geological series.

There are few formations that are entirely destitute of fossils, and in districts where the relative position of the rock-groups is for any cause obscure, or where their original order has been disarranged by the subsequent action of disturbing forces, it is chiefly by aid of their fossil contents that their true succession and superposition can be satisfactorily determined.

Practically it has been found that while a slight acquaintance with the characters of some fifteen or twenty of the commoner minerals is all that a geologist must necessarily learn of mineralogy, the number of animals and plants, with the forms and names of which he will have to make himself familiar, must be reckoned by hundreds.

From the foregoing remarks it will be seen that before we can properly understand the appearances presented by the rocks which compose the crust of the earth, we must have some knowledge of the agencies by which rocks are now being formed, and by which the form of the earth's surface is being modified. Again, before we can attempt to construct any history of the formation of the earth's crust we must be acquainted with the leading facts and conclusions of Palæontology, as that branch of the science is termed which deals with the structure and classification of former existences.

Descriptions of the various natural operations which are now in progress upon the earth, and of the changes which they bring about, were aptly termed by Sir Charles Lyell, "the Principles of Geology"; since it is only by a careful study of the changes which are taking place in the present that we can hope to interpret the many changes which have taken place in the past.

A knowledge of these first principles ought, therefore, to form the groundwork or introduction to the study of those subjects which are, perhaps, the more special province of geological science.

It seems, then, the most natural and logical treatment of the subject in the first place to describe the geological processes which can be seen at work in various parts of the world, and to show the student how these operations will explain the facts observable in the crust of the earth, and how they will account for the diversified features which its surface presents. By these steps we can proceed to the history of the earth since it became a habitable globe, as interpreted by means of the observations and deductions previously arrived at. This treatise, therefore, will be divided into five parts, which may be designated and defined as follow.

1. *Dynamical Geology.*—An account of the actual results produced by the geological agencies now in operation.

2. *Geognosy, or Structural Geology.*—Being the study of rocks and rock masses, without reference to the geological time of their production. This branch may be divided into two sections: *a. Lithology*—the study of the composition and texture of rocks as visible in detached specimens,

either by the naked eye or under the microscope. *b. Petrology*—the study of rock-masses, their structural characters, forms, and mutual relations, as visible *in situ*.

3. *Physiography*.—An explanation of the origin of hills and valleys, cliffs, escarpments, and mountains.

4. *Palæontology*.—Under this head will be given an outline of the laws which govern the distribution of life, both in space and time.

5. *Stratigraphy*, or *Historical Geology*.—Being a chronological account of the successive groups, or series of strata, which are found in the earth's crust. This will deal chiefly with the rocks of the British Islands, and will necessarily be only a condensed account, but prominence will be given to those facts which enable us to realize the relative positions of land and sea, and the general physical geography of each geological epoch.

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PART I.

Dynamical ~~PHYSICAL~~ GEOLOGY.

SECTION I. Changes produced by the Influence of Internal or Subterranean Causes.

CHAPTER I.

THE MASS AND GENERAL STRUCTURE OF THE EARTH.

THE Shape of the Earth, and its Consequences.—Everyone knows, or should know, that the earth has been both measured and weighed; and that the form of the globe is not that of a perfect sphere, but of an oblate spheroid. According to M. Bessel, the equatorial diameter of the earth is 7925·6 miles in length, while the length of the polar diameter is only about 7899·11 miles; the difference between them is, therefore, a little less than 26·5 miles. That is to say, that the polar axis is almost exactly $26\frac{1}{2}$ miles shorter than an equatorial axis or line passing through the centre of the earth from one side of the equator to the other: or, again, as calculated along radii from the centre, an equatorial radius is about $13\frac{1}{4}$ miles, or 70,000 feet longer than a polar radius.

If, therefore, a true sphere were to be described within the earth, with a radius equal to that of the polar radius, the surface of this sphere would lie at the depth of 70,000 feet below the actual surface at the equator.

Now the deepest soundings in the ocean are less than 30,000 feet, and the highest mountain in the world, viz., Mount Everest in the Himalayas, is only 29,000 feet above the sea. Compared, therefore, with the bulging protuberance of the earth's mass at the equator, the irregularities of its surface, which we know as ocean-depths and mountain heights, are obviously small.

It is also seen that this equatorial bulge of 70,000 feet, though only about $\frac{1}{300}$ part of an equatorial radius, repre-

sents the bulk or weight of an enormous mass of matter, and its existence involves very important consequences.

The first of these consequences is the stability of the earth's axis. The earth is a body which revolves upon its own axis, that is, upon an imaginary line connecting its two poles, and this line is its shortest diameter. The actual circumference of the earth's equator is about 83 miles greater than that of the true sphere enclosed by it, consequently its linear velocity is more rapid than that of the inner sphere, because any point on it is carried round that greater space in the same period of time. Any cause, therefore, which tended to make the earth revolve upon any other axis than that of its shortest diameter, would have to overcome the resistance of the greater momental force residing in the equatorial protuberance; and ever since the earth first acquired its present form, it is very difficult to imagine any cause sufficient to have produced this result.

Hence we may conclude that the position of the earth's axis has remained unchanged throughout all geological time, and that the present north and south poles have always been its poles.

The second conclusion deducible from the peculiar shape of the earth is the fact that it is almost exactly that of a spheroid of rotation; in other words, it is the form which the globe would have assumed had it been originally a pasty or fluid mass revolving with its present velocity. If a ball of molten matter were set to spin round one of its diameters as an axis, it would naturally tend to bulge about the parts farthest from that axis, the bulging being great in proportion to the velocity of its rotation, until for any given velocity a balance was ultimately produced between the centrifugal force of the rotation and the centripetal force due to the attraction of gravity in the mass.

The fact that the earth has this form raises a strong presumption that its condition was at one time sufficiently plastic to allow it to adjust its shape to the impulse of its motion; in short, that it was once in a semi-fluid or pasty condition. Although this original plasticity is by no means a certainty, yet it is generally assumed as a probability,

agreeing very well with some other known facts which are in favour of the idea, that the earth has been continually parting with heat, and that its own heat was once sufficient to keep its substance in a molten or semi-molten condition.

Internal Temperature of the Earth.—Without, then, further considering the question of the possible temperature and condition of the earth in the earliest times, we will pass to a subject with which geology is more directly concerned; viz., the probable state and temperature of its interior at the present time.

This is, of course, a very difficult matter upon which to obtain any evidence, but the following facts tend to show that it consists of a cool envelope surrounding a heated interior, and that the latter possesses a high temperature of its own, quite independently of any heat derived from the sun or other external source.

1. *Specific Gravity of the Earth.*—When we come to consider the mass of the earth, we shall find that its density is not so great as it would be if nothing impeded or counteracted the force of gravitation. This force would probably compress the rocks into a much closer and denser condition, and so cause the mass of the earth to have a greater density, unless there were some counteracting expansive force, and we know of no such force except that of *heat*.

2. *Volcanoes.*—The numerous volcanic orifices, which occur here and there all over the earth, and from which streams of lava or molten rock are so often poured forth, prove that some parts of the interior at any rate are so heated that solid rocks are rendered perfectly fluid. But the lavas derived from existing volcanoes form only a small portion of the bulk of igneous rocks in the crust of the earth, all of which have certainly come from the interior.

3. *Temperature of Deep Mines.*—The influence of the summer's heat or winter's cold does not penetrate far into the interior of the earth, and it is estimated that at a depth of about fifty feet beneath any given place on the earth's surface a thermometer would mark the same temperature all the year round.

Below this limit of seasonal variation, sometimes called "the stratum of invariable temperature," and as far as any mines or borings have been carried into the earth, the temperature of the rocks always increases with the depth. This downward increment of temperature is not the same at all places, being sometimes rather more and sometimes rather less than the average, but there are many causes which would tend to produce variations in the rate at which the temperature increases downwards.

Some of the earliest observations on the internal temperature of the earth were made by Mr. Henwood in the mines of Cornwall and Devon. The result of his experiments in two hundred of these mines showed that the average temperature at different depths was as follows:—

Depth.	Temperature.
At 200 feet	About 57° Fahr.
„ 600 „	„ 62° Fahr.
„ 900 „	„ 68° Fahr.
„ 1,200 „	„ 78° Fahr.

The average increase below 300 being about 1° Fahr. for every 43 feet of descent. In the granite rocks, however, the temperatures were not quite so high.

In a coal-mine at Monkwearmouth, Durham, the temperature at a depth of 1,600 feet ranges between 78° and 80°, and observations showed that the increase in descending from the surface was about 1° Fahr. for every 60 feet.

At the bottom of another deep coal-mine at Dukinfield, near Manchester (2,151 feet), the temperature is never more than 75° Fahr., which gives a less rate of increase, viz., 1° for every 80 feet.

In the Rose Bridge Colliery, near Wigan, however, a shaft has been carried down to a still greater depth, viz., 2,445 feet, and a careful series of observations were made by the manager, Mr. Bryham, during the process of sinking. The following are some of the results obtained:—

At a depth of 564 feet, a temperature of 66° F.
„ 1,674 „ „ 78° F.

At a depth of 2,013 feet, a temperature of 86° F.
„ 2,445 „ „ 94° F.

Assuming the surface temperature in this instance to be 49° F., these observations show an average increment of 1° for every 54½ feet of depth.

While, then, there is some variation in the rate of this increase at different places, it is an undoubted fact that the temperature of the rocks does always increase after passing below the first 50 feet; and it appears that the average rate of this increase of temperature may be taken at about 1° F. for every 60 feet of depth.

4. *Temperature of the water in deep wells and borings.*—The temperature of the water at the bottom of deep borings is in agreement with this conclusion.

The water of the artesian well of Grenelle, near Paris, which rises from a depth of 1,800 feet, has a constant temperature of nearly 82° F., which is about 29° hotter than the mean temperature of the ground beneath Paris, as ascertained in the cellar of the Observatory there. This, therefore, indicates a rate of increase of 1° for every 60 feet of depth.

Another well near Paris, at La Chapelle, where observations were taken at different depths, gave the following results:—

At	330	feet a temperature of	59½° F.
„	660	„ „	62° F.
„	1,000	„ „	65½° F.
„	2,200	„ „	76° F.

These figures yield a slower rate of increase, viz., only 1° F. for every 82 feet.

At Sperenberg, near Berlin, a boring was made to a depth of 4,172 feet, nearly all through rock-salt, and the temperature observed at a depth of 3,390 feet gave a result of 1° F. for every 51½ feet.

At Kentish Town (London) a well was sunk to a depth of 1,302 feet, and the temperature at the depth of 1,100 feet was found to be 69·9, giving a mean rate of increase from the surface of 1° F. for every 54 feet.

5. *Hot Springs.*—The Geysers and other hot springs

which are found in volcanic districts, must be regarded as deriving their heat from the volcanic focus, and cannot be taken as affording independent evidence of the internal temperature of the earth. Warm springs, however, are not confined to such districts, but often occur in localities which are far removed from any recent or recently extinct volcanoes. In our own country the waters of Bath, with a temperature of 120° F., and those of Buxton, with a temperature of 82°, are instances.

There is little doubt that the waters of these springs travel upwards through cracks and fissures, which originate at great depths, and that they are hot in consequence of the depth from which they come.

Weight or Mass of the Earth.—We began by saying that the earth had been weighed as well as measured. Its weight is generally expressed in the terms of its specific gravity. The specific gravity of a substance is its weight compared with that of the same bulk of pure distilled water at a temperature of 60° F. The specific gravity or mean density of the earth has been determined in several ways with results varying between 5 and 6; that is to say, its mass is between 5 and 6 times as heavy as an equal bulk of water, and we may consider its mean density to be about $5\frac{1}{2}$.

Now, most stones and rocks vary in their specific gravity from about $2\frac{1}{2}$ to 3, that of some of the most important rocks being given in the following table:—

Kind of Rock.	Mean Density.
1. Greenstone (Diorite)	3·0
2. Basalt	2·9
3. Granite	2·7
4. Marble	2·7
5. Slate	2·7
6. Sandstone	2·6
7. Chalk and Bath Oolite	2·5

That the mean density of the earth should be greater than that of the rocks at the surface is only natural, because the density of all rocks must be increased towards the centre of the globe by the pressure arising from the weight of the overlying rocks. It is more a matter of sur-

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prise that the mean density of the earth should not be greater than twice the density of rocks at the surface. For if the density increased in direct proportion to the pressure, *i.e.* if the density was doubled by doubling the pressure, it has been calculated that at the centre of the globe cold steel would be compressed into a fourth of its bulk, and most stone into an eighth. The mean density of the globe ought then to be about 11 instead of only 5 or 6.

Now, we have already seen that the interior of the earth may still have a very high temperature of its own, and if this be the case, the expanding force of heat would partially counteract the compressing force of gravity, so as to prevent the materials of the interior from being so greatly increased in density.

Lastly, it is possible that the heat of the interior may be so great as to entirely counteract the pressure, and if this is the case, the mean density of the earth may depend upon the existence in its interior of larger quantities of the heavier and less oxidizable metals than are found at the surface. The densities of the principal metals are as follows:

Metal.	Sp. Gr.	Metal.	Sp. Gr.
Platinum . .	21·5	Silver . . .	10·5
Gold . . .	19·3	Copper . . .	8·9
Mercury . .	13·6	Iron . . .	7·8
Lead . . .	11·3	Zinc . . .	6·8

The density at any point within the earth will depend therefore upon three things—(1) the nature of the material at that point, (2) the temperature, and (3) the pressure at the same point. We know that the two latter tend to counteract one another, but we do not know the exact amounts of either at any point, nor the result of their combined influence.

It is certain, however, that the earth does become gradually denser toward the interior. It is also certain that the increase of density is not directly proportional to the pressure, and experiments, as far as they have gone, seem to indicate that though the density does increase with the pressure, it does so at a continually diminishing rate, and that a point of approximate maximum density may be

reached, beyond which any additional pressure will not materially add to the density.

Laplace assumed that the law governing the relation between pressure and density within the earth is such that "the increase of pressure varies as the increase in the square of the density."[1]

This law may be otherwise expressed by saying that the increase of pressure for a given small increase of density is nearly proportional to the density. For instance, the increase of pressure on the density increasing from 2 to 2·1, compared with the increase of pressure on the density increasing from 3 to 3·1, will be nearly as 2 to 3. And in the same way, the increase of pressure on the density increasing from 3 to 3·1, compared with its increase on the density increasing from 4 to 4·1, will be nearly as 3 to 4, and so on. We see, then, that the pressure increases much faster than the density.

By employing Laplace's expression, the probable density at different depths has been calculated as follows,[2] taking the density of the surface to be 2·5:—

Density at depth of		250	miles	= 3·1
,,	,,	500	,,	= 3·8
,,	,,	1,000	,,	= 4·8
,,	,,	1,500	,,	= 6·4
,,	,,	2,000	,,	= 7·5
,,	,,	2,500	,,	= 8·5
,,	,,	3,000	,,	= 9·2
,,	,,	3,500	,,	= 9·6
,,	,,	4,000	,,	= 9·8

Internal Condition of the Earth.—The combined evidence of all the preceding considerations leads us to conclude that the interior of the earth is intensely hot.

Assuming the temperature of the invariable stratum beneath the British Isles to be 50° F.; that below this the increase of temperature continues indefinitely into the interior at the same rate as that which obtains in our mines

[1] Pratt's "Figure of the Earth," 4th edition, p. 113.

[2] Taken from Professor Green's "Physical Geology," third edition, 485.

and wells, viz., about 1° for every 60 feet or 88° for every mile, we should shortly arrive at a very high temperature.

At a depth of 9,620 feet or nearly two miles, the rocks would be as hot as boiling water, or 212° F.; at a depth of 30 miles they would be at a temperature of 2,690°, which is a heat sufficient to melt steel; and at 60 miles, a depth which is really only a little way towards the centre of the earth, we should find a temperature of 5,330°, which is a greater heat than any that we can produce at the surface.

It does not follow, however, as a necessary consequence that the materials which exist at these great depths would be melted at the same temperature that would fuse them at the surface, since the enormous pressure which they must sustain may keep them solid in spite of the heat.

It is well known that pressure retards or raises the melting-point of most solids, that is to say, an increase of pressure increases the temperature at which each is fusible. Very little, however, is known about the exact relations between pressure and the fusing-point of rocks, and it is possible that different substances are affected by pressure in a different ratio. Whether solid or fluid, we may safely assume that the interior of the earth has a very high temperature of its own, and if this is so, it must have been continually losing heat by conduction or convection from the interior to the surface, and this heat must have been dissipated into space. Consequently we are led back to the conclusion, which was foreshadowed on p. 11, that there was a time when the whole mass of the earth was in a molten or incandescent state, and that it has gradually cooled down to its present condition.

Assuming this to be the case, the condition of the earth's interior at the present time must depend upon the manner in which it has cooled, and Mr. Hopkins has shown that the earth's mass must now be in one of three different states; these are,[1]

1. A solid crust with a fluid interior.

2. A solid crust and a solid nucleus with a fluid interstratum.

[1] Phil. Trans. Roy. Soc., 1839.

3. Solid throughout, with or without fluid spaces or cavities.

Hopkins concluded that the balance of probability was in favour of the last (No. 3). He admitted,[1] however, that after the solidification of the nucleus there must have been a time when a solid external crust was formed resting on an imperfectly fluid mass beneath; but he thought that it must have grown to a thickness of not less than 800 or 1,000 miles at the present time, and that it had probably united itself to the internal nucleus.

He bases his opinion on the ground that the movements of precession and nutation could not be as they are, unless the crust possessed such a minimum thickness. Sir W. Thomson, however, has recently shown that these movements would still be experienced in the case of a thin crust covering a fluid substratum if the inner surface of the crust in contact with the fluid was not perfectly spherical. If this surface was only slightly irregular, the fluid and the crust "would have sensibly the same precessional motion as if the whole constituted one rigid body."[2]

Sir W. Thomson has nevertheless expressed his concurrence with Mr. Hopkins' conclusion that the earth is either solid or possesses so thick a crust as to give it practical solidity. He considers that the tide-producing power of the sun and moon is so great that if the thickness of the crust was less than 2,000 miles, it would yield to the strain, and would be subject to periodic deformations similar to oceanic tides.[3] He says that, "the solid crust would yield so freely to the deforming influence of the sun and moon, that it would simply carry the waters of the ocean up and down with it, and there would be no sensible tidal rise and fall of water relatively to land." He concludes that the mass of the earth "is on the whole more rigid than a continuous solid globe of glass of the same diameter."

Prof. G. H. Darwin has also investigated the tidal deformation of viscous spheroids, and his results tend to show that "no very considerable portion of the interior of the earth can even distantly approach the fluid condition."[4]

[1] Brit. Assoc. Rep., p. 48, note.
[2] Brit. Assoc. Rep., 1876. Sections, p. 5.
[3] Loc. cit., p. 7. [4] Phil. Trans., 1879, Part I.

Mr. O. Fisher, on the other hand, has recently published a most suggestive work on the "Physics of the Earth's Crust," in which he advocates the hypothesis of a thin crust with a thin liquid substratum and a large solid nucleus. Referring to the conclusions of Sir W. Thomson and Prof. Darwin, he says:[1] "It does not, however, appear necessary that the earth should be absolutely solid from the surface to the centre in order to satisfy these requirements. May not the argument for rigidity drawn from the tides . . . . be satisfied with a rigid nucleus of radius nearly approaching to that of the entire globe? Such tides as would be formed within the liquid substratum of the crust would not be of the nature of the tides contemplated by Sir W. Thomson as affecting the entire spheroid, but more nearly analogous to the ocean tides; since they would involve a horizontal transference of fluid backwards and forwards, and might be expected to be of small amplitude, owing to the viscosity of the substance and its confinement beneath the crust."

Assuming the existence of a continuous fluid, or at least plastic, substratum, Mr. Fisher adduces physical arguments for supposing that the thickness of the overlying crust is not everywhere the same; that its average thickness at the sea-level is about 25 miles; that it is thicker than this under mountain chains, and thinner under the oceans. To this question we shall have occasion to recur in the sequel.

In the present connection it is sufficient to note that if this theory of the earth's constitution be correct, a comparatively slight disturbance of the equilibrium of the crust would probably suffice to call forth some external symptoms of such an internal condition; and we should have a competent cause for igneous action and mechanical movement in the earth's crust.

As a matter of fact we know that such movements do take place all over the globe. Volcanoes pour forth vast quantities of molten matter; earthquakes shake large tracts of ground, and often produce permanent changes in the relative level of land and sea; and lastly, there is evidence to prove that slow and gradual movements of the crust have been in progress over still larger areas, the land

[1] "Physics of Earth's Crust," 1882, p. 23.

being elevated in one place and depressed in another. Finally it will appear that every part of the land has been below the sea at some period of past time, and is now dry land only because it has been elevated by the movements above mentioned.

It is desirable, therefore, that the student should be, in the first place, made acquainted with the nature and extent of these disturbances and the phenomena connected with them.

CHAPTER II.

VOLCANOES.

GENERAL Form and Structure.—A volcano may be defined as a conical pile of materials which have been ejected from the orifice of a pipe or fissure communicating with a highly heated portion of the earth's crust below. The materials composing the cone are chiefly stones and ashes which have been violently discharged into the air, and have fallen on all sides round the central orifice or *crater* as it is called. Every eruption adds to the pile and increases the height and magnitude of the volcano; great blocks as well as small stones, cinders, and ashes are thrown up and fall on all sides of the mountain. Floods of lava now and then boil up, and either break through the sides of the cone or run over the lip of the crater, and flow down into the adjacent country in the form of lava streams. Successive eruptions frequently take place from the same vent, but minor cones are often formed on the flanks of the larger one, and lesser eruptions proceed from them.

Volcanoes are sometimes isolated mountains like Vesuvius and Etna, but are more frequently arranged as a row of cones and peaks along straight or slightly curved lines, as if they had been thrown up at intervals along the course of great linear fissures in the earth's crust; such are the chains of the Andes, the Aleutian Islands, and the Malay Archipelago. These lines of volcanic vents sometimes seem to radiate from a special volcanic centre.

If we could make a vertical cut or section through a vol-

canic hill, so as to lay open its internal structure from the summit to the ground it rests upon, we should find this structure to be similar to that suggested in the diagram, fig. 1. At the base lies the platform of stratified rocks upon which the volcanic cone is reared. The parts shaded by vertical lines are intended to represent the lava-streams which have at different times issued from the crater and rolled down the surface slopes; the intervening parts, shaded with fine lines and dots, indicate the successive layers of stones and ashes which have been ejected from the central vent, and are disposed in more or less regular layers inclined at various angles, but all sloping away from the central axis. On either side are seen minor cones composed entirely of dust, cinders, and stones which have been thrown up from these lateral vents. Lastly, the lava which has risen from below is represented by the thick black lines which intersect the mountain in all directions.

It will readily be imagined that when molten lava is being forced up inside a volcano, some of it will be injected into any cracks or fissures which may exist, or which are caused by the impelling force. Sometimes the lava cools and solidifies in these cracks without making its way to the surface, forming veins or walls of solid stone which are called *dykes* by geologists. Such dykes occur by hundreds in every volcanic cone traversing the previously formed layers of ash and lava, and sending out smaller veins in all directions. Fig. 1 is of course merely a diagram, and the internal structure of a volcano is in reality much more complicated than is there represented.

Fig. 1. Ideal Section through a Volcanic Cone.

The appearance presented by some of the smaller veins and dykes of lava, exposed in the ravines which trench the sides of modern volcanoes, is shown in fig. 2.

Truncation of the Cone.—Sometimes a violent outburst of the volcanic force will blow the upper part of the cone completely away, and thus destroy what it has taken ages

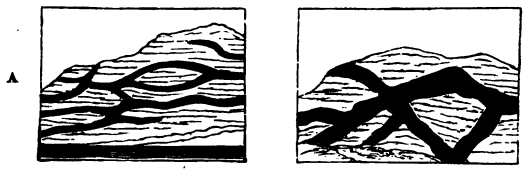

Fig 2. Veins and Dykes of Lava.
A. Veins of slaggy lava in volcanic tuff; Stromboli.
B. Dykes of lava in sand and scoriæ; Etna.

to build up. The volcano then presents the appearance of a truncated cone with a huge gaping hollow in the centre. Subsequent eruptions, however, repair the damage by forming a new cone in the interior of the great hollow; so that the mountain eventually consists of a lofty circular ridge surrounding a central depression, from the floor of which

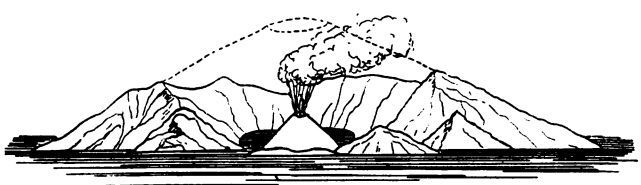

Fig. 3. Outline of Barren Island, after Scrope.

rises the new and active volcanic cone (as indicated in fig. 3). This formation of a new cone within an older truncated one is of frequent occurrence in the history of volcanoes. Vesuvius is known to have presented this appearance at several periods, and is even now partially surrounded by the old crater-ring called Monte Somma (see fig. 4).

Barren Island, in the Bay of Bengal, is an excellent instance of this form of volcano, as represented in fig. 3.

Here the whole central part of the mountain has been blown out by one tremendous explosion, the outline which the cone must have originally possessed being indicated by the dotted line.

The Peak of Teneriffe is another example in which the central cone rises far above the encircling ring of the older truncated mountain. This is well figured in Dr. Geikie's "Text-book of Geology."

Phenomena of an Eruption.—We now proceed to describe the succession of phenomena which usually take place during a volcanic eruption. The first intimations of the disturbance are generally loud rumbling sounds which seem to proceed from the interior of the mountain. Shocks of earthquake frequently succeed these noises; the water in wells and springs sink down in consequence of the opening of rents and fissures below; and finally, owing to the transmission of submarine shocks, the sea often ebbs and flows in an unnatural manner.

After these general disturbances, which are sufficiently alarming, the phenomena begin to be concentrated in the crater, and usually occur in the following order:—

1. An explosive discharge of steam, falling in rain.
2. A discharge of dust, ashes, and stones.
3. The ejection of larger blocks with heavier explosions: at the same time the red glow of the lava rising in the funnel lights up the vapour-clouds above, and produces the appearance of flames.
4. The lava rises and finds egress either from the crater or from lateral openings.
5. When the flow of lava ceases there is frequently a discharge of black sand or comminuted pumice. In some cases the eruption does not proceed farther than stage No. 2; but in violent eruptions there is a continued repetition of heavy explosions and outflows of lava.

Some volcanoes are in a state of constant activity, small explosions taking place incessantly at short intervals, while occasionally more violent outbursts occur, and streams of incandescent lava are poured forth. In other cases periods of quiescence alternate with periods of activity, and when eruptions do occur they are generally of a violent description.

From the records which we possess relating to the Italian volcanoes, it would appear that the same volcanic centre may exhibit both phases at different times; the eruptions being sometimes incessant and of moderate intensity for a long time, then ceasing, and a state of quiescence ensuing, which is broken by a more violent outburst. It has been noticed, indeed, that there is a distinct relation between the violence of an eruption and the length of the intervening periods of repose, so that the following rules may be laid down:[1]—

1. Feeble and short eruptions usually recur at brief intervals.

2. Violent or long-continued eruptions are generally followed by long periods of repose.

3. A long period of repose is generally succeeded by an eruption which is either of long duration or of great violence.

Products of an Eruption.—These may be classified and described in the following order:—1. Steam and gases; 2. Stones and ashes; 3. Lava.

1. *Steam and Gases.*—Steam is always discharged in great quantities during an eruption, bursting forth with a roaring sound from the crater, and sometimes also from vents and fissures on the sides of the mountain. The perpendicular uprush of steam from the crater spreads out above into a great horizontal cloud of vapour, the outline of the column and cloud together seen from a distance bearing much resemblance to that of a pine-tree very common in Italy, and known as the *stone-pine*.

Around this column vivid flashes of lightning are constantly playing, the electricity being produced by the friction of the uprushing current of steam as it escapes through the shaft or funnel of the volcano, and partly also by the collision of the fragments which are carried upward with it. The air at length becomes loaded with vapour which falls in heavy rain, thunder-storms are frequent, and great floods are thereby occasioned. The rain-water courses down the slopes and sweeps along the loose volcanic dust and ash, forming muddy torrents, which often work more damage and destruction than the streams of lava.

[1] See "Volcanoes," by J. W. Judd, p. 33.

Besides steam the following gases are emitted from volcanoes:—carbonic acid, hydrochloric acid, sulphurous acid, sulphuretted hydrogen, and boracic acid; together with hydrogen, nitrogen, and ammonia. By the action of these gases on the materials of the cooling lavas and surrounding rocks, a number of secondary products are formed, consisting of the chlorides and sulphates of various earths, sulphur and sulphides of certain metals. When sulphurous acid and sulphuretted hydrogen come into contact with each other, a chemical action takes place, which results in the formation of water and sulphuric acid, and the liberation of a certain amount of pure sulphur. This sulphur remains in the fissures and cavities where the combination takes place, the water is evaporated, and the sulphuric acid forms sulphates by combining with lime, iron, soda, and other substances.

2. *Fragmental Products.*—The solid materials ejected during an eruption are of various sizes and kinds. Some are fragments of the rocks which underlie the volcano, such as limestone or shale. These have been broken off, and blown out by the force of the explosions; but the greater number of the ejected fragments are pieces of molten rock or lava. The viscid scum which forms on the surface of the rising lava prevents the free escape of the steam which is constantly ascending through the mass; the steam, therefore, collects into great bubbles, which eventually burst, and the pressure being then relieved, a general escape of steam takes place with explosive violence, and fragments of the semi-liquid material are hurled high into the air. Among these there are sometimes blocks of large size, which, rotating as they rise, come to assume a spheroidal form; these are called *volcanic bombs.* Smaller cindery fragments are termed cinders or *scoriæ.* Some of these blocks and cinders fall outside the crater; but many fall inside, and are ejected again and again, hurtling against one another in the air, till they are reduced to fragments of still smaller dimensions (*lapilli*), while great quantities of mere dust and ash are produced at the same time.

The accumulations of coarser *débris* include fragments of all sizes, and form the rock known as *volcanic agglomerate.* The stones and cinders which fall on the inward slopes of

the crater roll down again into its mouth; and, at the close of an eruption, the crater and funnel are sometimes choked up with an agglomerate of these materials.

The rain, which is constantly falling during a long-continued eruption, mingles with the fine volcanic dust, and produces a peculiar pasty kind of mud, which sets into a firm, but light and porous stone, and is known by the name of *tuff* or *tufa*.

A strong wind blowing at the time sometimes causes a greater accumulation on one side of the mountain than on the other. The finer dust and powder is often ejected to such a height as to be carried by the wind for several hundred miles, and is thus spread out over a very wide space.

3. *Lavas.*—Lava-streams vary considerably in their degree of fluidity, and, consequently, in the rapidity with which they flow. In some cases, the lava is so liquid that it pours rapidly down the slopes of the cone like a river, and flows far out from the base of the volcano; but more usually it only preserves its fluidity for a short distance from the point of exit, a rough slaggy crust quickly forming over the surface of the *coulée*, though the lava beneath is still viscid, and the whole mass continues to move forward.

The crust of a lava-stream is sometimes wrinkled and twisted into *ropy* forms, such as are often seen on the surfaces of artificial slags; this is generally the case when the current moves slowly, and gives off but little steam or gas of any kind. More rapidly-moving currents always give off a larger amount of steam, the escape of which renders the crust vesicular and cindery, so much so that its surface is sometimes broken up by the rapid movement into large cindery blocks with sharp ragged projections. The lower end of such a stream has been described as a slowly-moving mass of loose porous blocks, gradually rolling and tumbling over each other, with a loud rattling noise, as they are forced along by the pressure of the viscid mass of cooling lava below.

As all rock is a bad conductor of heat, so, when the crust has once formed, the internal portion of the lava-stream always remains hot for a long period of time. The

process of solidification is, therefore, a very gradual one; and a great thickness of lava takes a proportionately long time to cool, and solidify into stone. Natural sections of lava-streams in cliffs or ravines show that the upper and lower layers of the cooled mass are always more or less vesicular and scoriaceous, while the central portion is a hard, compact, and frequently a crystalline stone.

The gradual cooling of the lava causes it to contract, and leads to the production of cracks, which traverse the whole mass from top to bottom. These are sometimes so regular as to split the mass up into a series of hexagonal prisms or rude columns, similar to those assumed by starch and other substances in passing slowly from a fluid to a solid state. This structure will be more particularly described in Part II.

Slow-moving lavas are frequently congealed before they arrive at the base of the cone, but the more liquid lavas often flow to a distance of many miles from the point of eruption. Lava-currents from Vesuvius are said to have flowed a mile and a half in fourteen minutes, and others a distance of nearly two miles in the space of three hours. The stream which issued from one of the lateral cones of Etna, and destroyed Catania in 1669, was 14 miles in length, with a width of 5 miles in some places. The floods of lava, however, which issued from Skaptar Yokul in Iceland, in the year 1783, are the most extraordinary on record. One of these lava-streams was 50 miles long, with a width of from 12 to 15 miles; another was 40 miles long, with an occasional width of 7 miles; both had an average depth of 100 feet, increasing here and there in narrow ravines to a depth of 500 or 600 feet.

Connection of Volcanoes with Lava-filled Fissures.—The position which volcanoes apparently hold in relation to lines of fissure in the earth's crust has already been mentioned; and the dykes which traverse the cone itself have been spoken of as cracks injected with lava. The actual formation of such fissures has, indeed, been observed; and Sir Charles Lyell gives the following account of one which opened in the plain of St. Lio, near Etna:[1]—

[1] "Principles of Geology," tenth edition, vol. ii. p. 21.

"A fissure 6 feet broad, and of unknown depth, opened with a loud crash, and ran in a tortuous course to within a mile of the summit of Etna. Its direction was from north to south, and its length 12 miles. It emitted a most vivid light, indicating that the fissure was filled with incandescent lava, probably to the height of an orifice not far from Monte Rossi, which at that time opened and poured out a lava-current. When the melted matter in such a rent has cooled, it must become a solid wall or dyke, intersecting the older rocks of which the mountain is composed." There is every reason to believe that the fissures over which volcanoes stand are similarly filled with molten rock, and are, in fact, the feeders or reservoirs of the volcanic vents. On the cessation of volcanic activity in the district these lava-filled fissures must remain as enormous dykes, extending for long distances, and cutting through all the rocks of which the country is composed. Such dykes are sometimes found extending for distances of 50 or 100 miles across the country; and in Iceland, during the eruption of Skaptar Yokul, in 1783, "lava was emitted consecutively at several points on a linear range of 200 miles," a lava-filled fissure doubtless extending throughout the whole of this distance, and now remaining as a solid dyke.[1]

Such dykes, as Lyell observes, may be called the roots of the volcano, reaching downwards to the regions of subterranean fire, while the external cone, with its lava-streams and loose ashes, may be likened to the branches and light foliage; and, to complete the simile, we may consider the central pipe or chimney to be the stock or trunk of the volcanic tree through which the lava-sap rises from the deep-seated roots to feed the sub-aerial branches.

Examples of Volcanic Action.

Vesuvius and the Phlegræan Fields.[2]—The volcanic region of Naples consists of a linear group of cones, ranging N.E. and S.W., and terminated at its extremities by the two

[1] Scrope, "Volcanoes," p. 52.

[2] The following descriptions are selected from those in Mantell's "Wonders of Geology," seventh edition, p. 843 *et seq.*, and are chiefly compiled from the writings of Mr. Poulett Scrope.

principal mountains, Ischia and Vesuvius; the latter seems to be connected by the intervention of minor vents with the group of Albano and of Rome—the seven hills of the Eternal City being for the most part volcanic mounds.[1]

The celebrated mountain of Vesuvius is about 4,000 feet high, and its general outline is exceedingly regular, though its summit is now broken and truncated. Mr. Scrope observes that this regularity is owing to the great fluidity of its basaltic lavas, which, issuing from the central vent, have taken their course in spreading sheets down the outer slope of the mountain, while the scoriæ and fragmentary substances projected at the same time into the air were spread pretty evenly over them.

"The result of successive eruptions of this kind has been the formation of a regularly conical mountain, with a gradually diminishing slope on all sides, from the central heights to the plain around, exhibiting in the ravines that furrow its sides, as well as in the abrupt sections afforded by the walls of the great crater, its composition of repeatedly alternating beds of basalt and basaltic conglomerates more or less irregular in thickness, but dipping uniformly on all sides away from the vent, with an inclination corresponding exactly to the external slopes of the mountain.

"The eruptions of Vesuvius seem very rarely to have taken place from any other than the central vent; a few small cones immediately above Torre del Greco thrown up in 1794, and the cone on which the Camaldoli della Torre is built, are the only indications of explosions having burst from the sides of the mountain. The vast number of vertical basaltic dykes which intersect the horizontal beds observable in broken cliffs of the old crater (Atrio del Cavallo), bear witness, however, that the lava was not so frequently elevated to the summit of the mountain without occasioning numberless cracks and rents in its internal structure.

"The old crater of Somma, whose steep walls now half encircle the cone of Vesuvius (see fig. 4), was formed by the celebrated eruption of the year 79, which occasioned

[1] See Murchison, "Quart. Journ. Geol. Soc.," vol. vi. p. 281.

the death of the elder Pliny, and buried Herculaneum, Pompeii, and Stabiæ beneath a bed of ashes and fragmentary scoriæ from 30 to 100 feet in thickness."

When Italy was first colonized by the Greeks, Vesuvius was in a quiescent or dormant state, while the neighbouring isles of Ischia and Procida were the theatres of constant earthquakes and explosions: but since Vesuvius has resumed its activity, Ischia has been almost entirely dormant. Ischia has numerous cones; the central one, Epomeo, is 2,600 feet high, and has traces of two large craters on its summit; but eruptions have burst out at various points,

Fig. 4. View of Vesuvius, looking over the plain of Pompeii.

and a lava-stream that issued from its base still exhibits an arid and cindery surface.

The Lipari Isles between Naples and Sicily, lying, as it were, midway between Vesuvius and Etna, present a character very analogous to the district above described.

The crater of one of the islands, Stromboli, has been in constant activity from the earliest historical period. It always contains melted lava in constant motion, and at uncertain intervals the molten mass suddenly rises, and large bubbles appear, which, upon reaching to the brim of the crater, explode with a sound resembling thunder;

masses of lava, with dust and smoke, are thrown into the air, and the incandescent fluid then sinks down to its former level.

The cliffs of St. Calogero, which are about 200 feet high, and extend four or five miles along the coast, consist of horizontal beds of volcanic tuff, traversed in every direction by dykes and veins of lava (see fig. 2, A).

Etna.—This volcanic cone rises majestically to the height of more than two miles (10,872 feet), the circumference of its base exceeding 180 miles. Compared with this prodigious mass of igneous products, Vesuvius sinks into insignificance, for while the lava-streams of the latter do not exceed seven miles, those of Etna are often from 15 to 30 miles in length, and from 50 to 100 feet in thickness. The surface of Etna presents three distinct regions; around the lower slopes the country is richly cultivated, and abounds in vineyards and pastures, towns and villages; the middle or temperate zone above is covered with forests of oak and chestnut; but upwards the trees grow sparse and small, and the last 5,000 feet form a bare and sterile region, while the summit is capped with eternal snow.

As a volcano Etna possesses two remarkable features—1. The number of minor cones which have been thrown up on its flanks, no fewer than 200 such lateral vents being known. In 1809 twelve new craters opened about halfway down the mountain, and threw out copious streams of lava; again, in 1811, other vents appeared on the eastern side.

2. But by far the most interesting feature of Etna is an immense depression or excavation on the eastern side of the mountain, called the *Val del Bove*. This vast hollow is 5 miles across, and its sides are precipices from 2,000 to 3,000 feet in height.

There is good reason to believe that the Val del Bove contains the site of a second focus of eruption, and that the materials which once occupied it were blown away by explosions similar to those which removed the central portion of Somma, before the modern cone of Vesuvius was built up. If so, the new cone, which forms the present summit of Etna, did not rise within the old crater, but quite outside its limits. Other cases, in which the volcanic

focus has shifted its position, are not rare, and examples are found in Vulcano and Vulcanello, two of the Lipari islands.[1]

The perpendicular sides of the Val del Bove are everywhere marked by vertical walls or dykes, which not only intersect the concentric sheets of lava and tuff, but, standing out in bold relief, like prodigious buttresses, impart a most extraordinary character to the scene. These buttresses are from two to twenty feet in thickness, and their superior hardness has enabled them to resist the action of rain and frost better than the less coherent tuffs around them.

The floor of the great hollow forms a desolate plain. Innumerable currents of lava have flowed into it, and some have advanced across it, and descended, cascade-like, into the lower fertile regions, where they are spread out in sterile tracts, amid the vineyards and orange-groves.

Hawaii, one of the Sandwich Islands, contains three volcanoes called Mount Kea, Mount Loa, and Mount Hualalai. The first is extinct, the two latter active, and they all unite in presenting several points of difference from the volcanic cones already described.

In the first place, they are almost entirely composed of lava flows, and the lava they emit is particularly liquid, so that it flows for long distances, consequently the outline of the hill is low and broad, as indicated in fig. 5, with an average slope of less than 10 degrees. The cones of such mountains as Etna and Vesuvius are mainly composed of cinders and tuffs, and their slopes are consequently much steeper, varying generally from 25 to 30 degrees, and in some places being as much as 35 or 38 degrees.

Secondly, the phenomena of an actual eruption are very different; it is seldom preceded by earthquakes, or by any of those violent eruptions of steam, cinders, and stones, which are so characteristic of other volcanoes; and, finally, the emission of lava takes place, not over the lips of the crater, but through a rent or aperture in the side of the mountain. The whole eruption is therefore of a much less violent and destructive nature.

The cause of these differences appears to lie in the ex-

[1] See "Volcanoes," by J. W. Judd, for illustrations of this and other features of volcanoes.

treme liquidity of the lava, through which the pent-up steam and vapour can make its way to the surface much more easily than it can through the more viscid lavas of other volcanoes. The latter exhibit scenes of more violent activity, because the vapours are confined, and accumulate

Fig. 5. Outline of Mount Loa.

in enormous bubbles, which increase until they gain sufficient force to blow out the overlying column of lava, and shatter it into fragments. Hence the formation of fragmentary deposits on the surrounding slopes, which are absent in the case of the Hawaian volcanoes.

Fig. 6. View of the crater of Kilauea.

Mount Loa is about 14,000 feet high; it has a crater at the summit, and another much more active orifice, called Kilauea, far down its eastern slope, and only 4,000 feet above the sea. The actual cause of an eruption seems to be hydrostatic pressure; the lava rises and accumulates in

the central funnel, and the pressure exerted by this column gradually increases until the sides of the mountain can no longer resist it, but crack, and so give issue to the fluid material at one or more points along the line of fissure.

Kilauea is a great pit, from 2 to 3 miles wide, and about $7\frac{1}{2}$ miles in circumference. After an eruption the depth of this pit, owing to the subsidence of the lava, is sometimes as great as 1,000 feet, but it gradually fills up again until it is only 500 or 600 feet deep. An eruption may then be expected; an addition of 400 feet to the column of lava within the crater causes a corresponding increase of pressure, and eventually one or more fractures are produced below the crater, through which the lava makes its way to the surface. During the eruption of 1868 the lava first rose to a great height in Kilauea, and then broke out at several points one below the other, finally issuing in a continuous stream at a place about 20 miles from the sea, into which it flowed at Nanawale; other lava flows from higher levels below the summit crater of Mount Loa can be traced for distances of 30 or 40 miles down the flanks of the mountain.

Volcanic Islands and Submarine Volcanoes.—A volcanic island may have originated in two ways, it may be either the highest peak of a sunken tract of land, and therefore an island, because the sea has overflowed the ground on which it stands; or, it may have been built up from the sea-bottom, repeated eruptions increasing the height of the volcano till it lifts its head above the waves and becomes an island.

An interesting example of the latter kind of volcanic island was formed in the Mediterranean about 30 miles off the south-west coast of Sicily during the summer of 1831, at a spot where previous soundings had ascertained the depth of the sea to be 600 feet. Its formation was preceded by a violent spouting up of steam and water, and the sea around was covered with floating cinders and shoals of dead fish. At length a small island gradually appeared, having a crater on its summit which ejected steam, ashes, and scoriæ. This crater attained an elevation of nearly 200 feet, with a circumference of about 3 miles, having a circular basin full of boiling water of a dingy red colour.

The island received various names, but is best known by the English one of "Graham's Island," and the French one of "l'Isle Julia." It continued in activity for three weeks and then gradually disappeared. In 1833, two years after its destruction, a dangerous reef remained 11 feet under water, in the centre of which was a black volcanic rock (probably the remains of the plug of lava in the crater), surrounded by shoals of scoriæ and sand.

During the gradual building up of such a submarine volcano, the lava-streams and fragmental materials which are ejected into deep water, are probably arranged in much

Fig. 7.—Graham's Island in 1831, from a sketch by M. Constant Prevost.

the same manner as those which fall on land. Some opportunities have occurred for observing the flow of lava beneath water, and it has been noticed that the crust which rapidly forms over the surface prevents the water from coming in contact with the internal fluid portion of the stream. The escape of heat is also checked by the low conducting power of the crust, and so the interior remains fluid, and continues to flow onward, just as it would do on land. Professor Green has even surmised that, "if the discharge takes place in deep water, it is conceivable that the pressure of the overlying fluid will check the escape

both of elastic fluid and of heat from the lava, and so keep it fluid for a longer time, and cause it to spread out in wider and more regular sheets, than if it had flowed out in the open air."[1]

Again, the ash and cinders ejected from such submarine vents will probably arrange themselves on the slopes of the cone, and form beds of tuff and agglomerate, similar to those of sub-aerial origin. But the case is different with the ejections from volcanic islands, because such of these as do not fall on the slopes of the island itself will drop into the shallow waters surrounding it, and will be subjected to the distributive action of the sea-waves, tides, and currents. They will be arranged and stratified on the sea-bottom, and will often be mixed with the other deposits which are there being formed. Arenaceous or calcareous tuffs may thus be produced by the admixture of sand or limestone. Moreover, in all such submarine tuffs, fish, shells and other marine remains are liable to be enclosed, and will testify by their presence to the conditions under which the stratified masses have been accumulated.

Many of the solitary volcanic islands which occur in the midst of the Pacific and Indian Oceans, such as Barren Island (fig. 3), Isle of Bourbon (Réunion), and St. Paul's Island, may have originated in the manner above described.

The small islands of Santorin and Therasia in the Ægean Sea, have been explored by Admiral Spratt and Professor E. Forbes (1841), and more recently by M. Fouqué (1880).[2] These two islands form the crater rim of a partially submerged volcano, which is still occasionally active; the modern eruptions proceeding from small islands thrown up in the central lagoon. Marine shells have been found in the tuffs of Santorin up to a height of 600 feet above the sea, proving that elevation to that extent has taken place since volcanic action began.

[1] Green, "Physical Geology," second edition, p. 225.

[2] See Lyell's "Principles," tenth edition, vol. ii. p. 66, and Fouqué's "Santorin et ses Eruptions," Paris, 4to. 1880.

CHAPTER III.

EARTHQUAKES.

CONNECTION between Volcanoes and Earthquakes.—Before the bursting out of any great volcanic eruption it almost invariably happens that the neighbourhood is shaken by earthquakes, as if by the struggles of the volcanic force to find a vent (see p. 23).

It has also been observed that a succession of earthquakes in one district has been closed by a great volcanic eruption in some neighbouring district.

The connection between volcanoes and earthquakes was exhibited in a remarkable manner by the series of events which took place in and around the Gulf of Mexico at the beginning of this century. From May, 1811, to April, 1812, severe earthquakes were felt in the West India Islands, especially in St. Vincent; violent shocks also occurred in the Mississippi valley, and at Caraccas in Venezuela; finally, on April 30th, 1812, the volcano of St. Vincent, which had been quiescent for nearly a hundred years, burst into eruption.

So tremendous was the explosion that the noise of it was heard at Caraccas, nearly 500 miles away, but with it the movements in South America ceased for the time.

The connection between the two sets of phenomena is also shown in other ways. Mr. Mallet[1] has studied the extent of the areas which are most frequently and violently disturbed by earthquakes, and finds that these areas form bands of great but variable breadth, within which the seismic influence is sensible for a width of from 5 to 15 geographical degrees of longitude.

He prepared a map of the world on which the districts known to have been shaken by earthquakes were coloured brown, the tint being made darker and darker in proportion to the frequency and intensity of the shocks which had been experienced at different localities.

[1] "Catalogue of Earthquakes," Brit. Assoc. Reports, 1847 to 1861.

A glance at such a map shows that the bands of darkest colour run along the mountain chains on which volcanoes occur; and Mr. Mallet has formulated the following conclusions:—

1. These seismic bands very generally follow the lines of elevation which mark and divide the great oceanic or terr-oceanic basins of the earth's surface.

2. In so far as these are frequently the lines of mountain chains, and these latter often include lines of volcanic vents, so the seismic bands follow them likewise.

3. The sensible width of the seismic band depends upon the energy developed, and on the accidental geological and topographical conditions along its length.

4. Seismic energy may become sensible at any point of the earth's surface, its efforts being, however, greater as the great volcanic lines of activity are approached.

Nature and Origin of Earthquakes.—Mr. Mallet[1] defines an earthquake as a wave of elastic compression or a succession of such waves traversing the crust of the earth with immense rapidity.

This wave is transmitted from a subterranean *centre of impulse* (*a* in fig. 8), which Mr. Mallet treats as a rent or fissure, and it proceeds from that focus with equal velocity in every direction. The line along which the wave reaches the surface directly over the centre of impulse, Mr. Mallet calls the *seismic vertical* (*a b*), and the concentric lines along which the shock reaches the surface at the same moment he calls the *coseimal lines* (*c c*, *d d*); the wave strikes the surface more and more obliquely as we recede from the line, *a b*, and with less and less force, till it gradually fades away. By observing the direction of fissures and by the use of instruments called *seismometers*, Mr. Mallet shows how it is possible to determine the direction and the angle of emergence of the wave-path, and thus to calculate the position and depth of the centre of impulse from which the wave proceeded. By this method Mr. Mallet calculated that the centre from which the shock of the great Calabrian earthquake in 1857 proceeded, was beneath a spot about 60 miles E.S.E. of Naples, and

[1] "First Principles of Observational Seismology."

at a depth of about 5½ miles from the surface. He assigns 30½ geographical miles, or 185,000 feet, as the limit of depth at which any earthquake originates.

In fig. 8, the centre of impulse is represented as a point, and it is assumed that the surrounding rocks are homogeneous, so that the coseimal lines are circles. In reality, however, the centre of impulse must generally be a narrow fissure of some length, and the impulse will generate waves proceeding outwards from the surface of the fissure in ellipsoidal shells, the coseimal lines being ovals whose major axes are at right angles to the plane of the fissure. The variation in the density and elasticity of the rocks through which the wave passes, also interferes with the

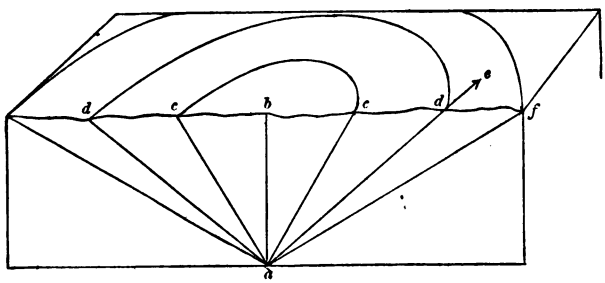

Fig. 8.

regularity of the coseimal lines, and the passage of the wave from one kind of rock to another causes refractions, so that the actual form of the wave at the surface is complex and irregular.

The earth-wave travels most rapidly through hard and compact rocks, less rapidly through soft and incoherent beds. Mr. Mallet has experimented by exploding gunpowder and calculating the velocity of the shock so produced in different rocks. He found that the wave traversed—

Solid granite	at a rate of	1,665	feet	per second.
Shattered granite	,,	1,306	,,	,,
Slate ,,	,,	1,089	,,	,,
Wet sand ,,	,,	825	,,	,,

The effects of the wave are more destructive when it traverses soft rocks because the cracks which it produces at the surface are kept open for a longer time, and allow buildings to subside; while in hard rocks these fissures are narrower and close more quickly, so that less displacement is caused. When the wave passes from compact into loose rocks, there is often a complex reflection and reverberation of shocks which results in a destructive shivering of the surface.

If the angle of emergence is low, the difficulty which the wave finds in passing from hard into overlying soft rocks is such that a very small shock is propagated through the latter. Thus the Lisbon earthquake was felt in Scotland, but not in England, and the reason is supposed to be that the wave travelled through the hard rocks at a great depth below the ground, and the slight shock communicated to the thick mass of softer rocks which form the greater part of England died away before it reached the surface.

Phenomena and Effects of Earthquakes.—The phenomena attendant upon an earthquake shock vary according as the centre of impulse is under the land or under the sea. In the first case waves are only propagated through the earth and through the air: in the second case the waves are communicated to three media, viz., earth, air, and water. Moreover, sound-waves appear to be through the earth and the sea, as well as through the air, so that if the shock originates under the sea, an observer standing near the shore will perceive the following succession of phenomena.

1. A rumbling noise, heard apparently through the feet; this being the sound-wave through the earth, which is said to travel at a rate of 11,000 feet per second.

2. Another sound caused by the sound-wave through the air, which travels at the rate of 4,700 feet per second.

3. The earth-wave, bearing with it a small forced sea-wave; its velocity varying, as already stated, from about 800 to 1,600 feet per second (mean rate about 1,200 feet).

4. A third sound produced by the sound-wave through the air, which is carried 1,138 feet per second, and therefore is sometimes heard at the same time as the earth-wave is felt.

5. The great sea-wave, the sea being first sucked back for some distance from the shore, and then returning as a wall of water from 15 to 20 feet high, rolling in far over the land and washing down everything before it. The first is often followed by smaller waves.

The velocity of the sea-wave depends upon the depth of the water through which it is propagated; it travels through deep water much faster than through shallow water near the land. Thus the sea-wave of the Lisbon earthquake in 1755 travelled to London at a little over 2 miles a minute, but crossed the Atlantic to the Barbadoes at a rate of about 5 miles per minute. The wave which travelled across the Pacific from Japan to California in 1854 had an average velocity of 6·1 miles per minute.[1]

Calabria.—The earthquakes which convulsed Calabria in 1783 were remarkable for the number of separate shocks (949) that occurred during the year, and for the great disturbances and changes which they produced on the surface of the ground. The area over which these shocks exerted their most violent effects was not more than 500 square miles, but they were perceptible over a great part of Sicily, and as far north as Naples.

In some of the Calabrian towns the pavements were thrown into the air and reversed so as to lie bottom upwards. Long undulating fissures were formed, some of which remained open, and some gradually closed up again. The wells and springs were violently disturbed, and in some places circular cavities were opened from which water escaped, and which afterwards remained in the form of pools.[2]

In the town of Terranuova some houses were elevated above their former level, while others sunk below it, and one tower of solid masonry was divided into two parts by a crack, on one side of which the building was elevated several feet above the other part. This vertical shift was rendered apparent by the discontinuity of the courses of stone, which presented a counterpart of the dislocation which must have been produced in the rocks below, and which is termed a *fault* by geologists.

[1] From this it has been calculated that the mean depth of the body of water through which it moved, viz., the North Pacific, was 14,190 feet.

[2] See the account in Lyell's "Principles," vol. ii. ch. xxix.

Great masses of earth and rock slid down from the sides of the valleys, and some of these landslips dammed up the rivers, and gave rise to new lakes. Thus enormous masses of land were detached from each side of the deep valley or ravine of Terranuova, and blocked up the course of the river, causing the formation of a large lake. It is stated that about fifty such lakes were formed at this time; some of these were permanent, the course of the streams being altered, but others were gradually drained by the water overflowing and cutting a channel through the barrier. Along the sea-coast huge masses were detached from the cliffs, especially at Scilla and at Gian Greco in the Straits of Messina, where a continuous line of cliff was thrown down for the length of a mile.

South America.—In the earthquake of Quito, on February 4th, 1797, the velocity of the shock was so great that Humboldt says the "explosive movement was such as is produced by the firing of a mine, and the bodies of several of the inhabitants were thrown upon the hill of La Cullca, which rises on the other side of the Lican torrent." The actual range of vertical projection of these bodies has been calculated, according to Mr. Mallet, at 100 feet, which he says would give a velocity of shock equal to 80 feet per second.

The centre of the disturbance seems to have been the volcano Tunguragua, and the district most violently shaken measured 120 miles from north to south, and 60 miles from east to west, but the shocks were felt far beyond these limits. Riobamba and all the other towns within this area were destroyed. The ground about Tunguragua opened into enormous clefts, from which issued volumes of water and stinking mud, forming lakes in many places of considerable size.[1]

Another of the great earthquakes which so frequently shake the western coast of South America happened on the 20th of February, 1835. It was felt in all places between Chiloe on the south and Copiapo on the north, a distance of more than 1,000 miles, and between the city of Mendoza on the east and the island of Juan Fernandez on the west,

[1] Humboldt's "Voyage," p. 317.

a distance of at least 600 miles. Admiral Fitzroy, who was at Talcahuano, the port of Concepcion, says that after the earthquake there was a belt of coast 4 or 5 feet in height, which, even at high water, showed beds of dead mussels, limpets, and withered sea-weed, all still adhering to the rocks. This raised beach gradually sank again until the part above high-water mark was not more than 2 feet high. He also visited the neighbouring island of Santa Maria, where he found that the following changes had taken place. "It appeared that the southern extremity of the island had been raised 8 feet, the middle 9, and the northern end upwards of 10 feet. On steep rocks, where vertical measures could be correctly taken, beds of dead mussels were found 10 feet above high-water mark. An extensive rocky flat lies around the northern parts of Santa Maria. Before the earthquake this flat was covered by the sea, some projecting rocks only showing themselves. Now the whole flat is exposed, and square acres of it are covered with dead shell-fish, the stench arising from which is abominable."[1]

Speaking of the same earthquake the late Dr. Darwin says:[2]—"The island of Quiriquina plainly showed the overwhelming power of the earthquake. The ground in many parts was fissured in north and south lines, perhaps caused by the yielding of the parallel and steep sides of this narrow island. Some of the fissures near the cliffs were a yard wide. Many enormous masses had already fallen on the beach; and the inhabitants thought that when the rains commenced far greater slips would happen. The effect of the vibration on the hard primary slate, which composed the foundation of the island, was still more curious: the superficial parts of some narrow ridges were as completely shivered as if they had been blasted by gunpowder. This effect, which was rendered conspicuous by the fresh fractures and displaced soil, must be confined to near the surface, for otherwise there would not exist a block of solid rock throughout Chile; nor is this improbable, as it is known that the surface of a vibrating body is affected dif-

[1] Phil. Trans., 1826, and Lyell's "Principles," tenth edition, vol. ii. p. 93.

[2] "Voyage of the Beagle," edition of 1860, p. 393.

ferently from the central part. It is, perhaps, owing to this same reason, that earthquakes do not cause quite such terrific havoc within deep mines as would be expected. I believe this convulsion has been more effectual in lessening the size of the island of Quriquina, than the ordinary wear-and-tear of the sea and weather during the course of a whole century."

New Zealand.—A great earthquake occurred in New Zealand in 1855, during which a tract of land comprising 4,600 square miles is believed to have been permanently upraised; Sir C. Lyell states on the authority of Mr. Edward Roberts, R.E.,[1] that the amount of elevation increased eastward and attained its maximum along the Rimutaka range near Port Nicholson, where the elevation was 9 feet. The

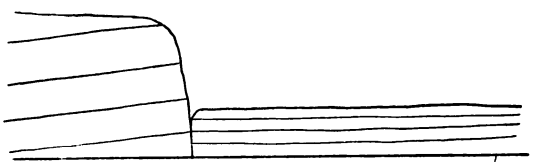

Fig. 9. The Upheaval of the Rimutaka hills, after Lyell.

land on the west side of these mountains, forming the plain of Wairarapa, was not raised at all, the vertical movement ceasing abruptly along the base of the hills, and forming a line of fault or fracture which was traced for a distance of 90 miles.

The course of the fault along the base of the hills was rendered visible by a nearly perpendicular cliff of fresh aspect about 9 feet in height. It was marked moreover in many places by fissures from 6 to 9 feet broad, filled here and there with soft mud and loose earth. The relations of the rocks on either side of this fault are indicated in the diagram, fig. 9, the hard rocks A being elevated, while the newer, B, remained horizontal. Previous to the earthquake there had been no room to pass between the sea and the base of the perpendicular cliff in which the Rimutaka range terminates in Cook's Strait, except for a short time at low

[1] Lyell's "Principles," tenth edition, vol. ii. p. 85.

water; "but immediately after the upheaval a gently sloping raised beach, more than 100 feet wide, was laid dry, affording ample space at all states of the tide for the passage of man and beast."[1]

Bay of Baiæ.—One of the most interesting examples of local subsidence and subsequent upheaval is that afforded by the remains of the celebrated temple of Jupiter Serapis at Puzzuoli.

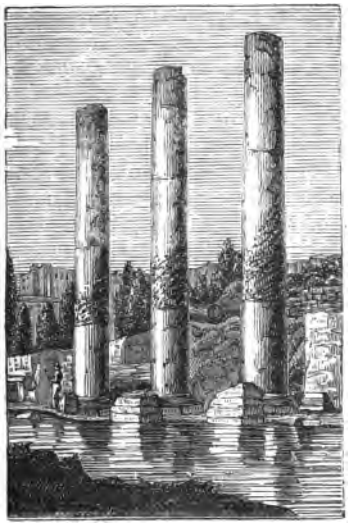

Fig. 10. Remains of the Temple of Jupiter Serapis, after Lyell.

The ruins of this building were discovered about the middle of last century, and excavations disclosed a square floor which had originally supported forty-six noble columns, twenty-four consisting of granite, and twenty-two of fine green marble. Only three of these remain erect, and are little more than 40 feet high. Up to a height of about 12 feet from their pedestals their surface is smooth and uninjured, but above this level there is a band or zone, about

[1] Lyell, op. cit. vol. ii. p. 86.

9 feet in height, where the marble has been perforated by a boring mollusc (*Lithodomus dactylus*), the shells of which are still to be found at the bottom of the holes. These molluscs are common in the Mediterranean, and bore their way into limestone rocks just as the "shipworm" does into timber.

Evidence of a still earlier subsidence was discovered in 1828 by excavations below the marble pavement on which the columns stand, a second mosaic pavement being found at a depth of 5 feet below the upper one. The existence of this lower pavement clearly implies a subsidence which rendered it necessary to construct a new floor at a higher level.

The temple area was filled with a succession of stratified deposits, consisting of marine and fresh-water limestones with two layers of volcanic tuff, ejected, probably, from the neighbouring crater of the Solfatara. These beds concealed the lower part of the columns up to the base of the perforated band, and the perforations were thus evidently made during a subsequent subsidence of 9 or 10 feet; for since it is only that particular part of the column which is perforated in the manner described, we may fairly conclude that the lower portion was protected from their attacks by the accumulation of sediment, and that the upper part at the same time projected above the surface of the sea.

The upper limit of the perforations was, in 1828, about 23 feet above the level of the sea, so that there had been an elevation of the whole area to at least this extent. This upheaval appears to have taken place during the 16th century, for two documents are cited in which Ferdinand and Isabella of Spain grant to the University of Pozzuoli a portion of land "where the sea is drying up" (1503), and again, "where the ground is dried up" (1511). This seems to indicate that a slow and gradual upward movement was taking place during this period, but it is probable that the principal elevation took place at the time of the great eruption of Monte Nuovo in 1538. Two eye-witnesses of this convulsion declare that the sea then abandoned a considerable tract of the shore.[1]

[1] "Principles of Geology," tenth edition, vol. ii. p. 174.

The oscillations of level which appear to have occurred in this area during historic times may therefore be thus summarized:

1, Subsidence of 5 feet between the two pavements.

2. Period of rest, the temple built.

3. Gradual subsidence of 12 feet, and deposition of sediment; subsidence continued for 9 feet without deposition.

4. Period of rest, and perforations made in the columns by boring molluscs.

5. Gradual upheaval to extent of more than 23 feet.

6. Slight subsidence again at the beginning of the present century.

Summary of Surface Effects produced by Earthquakes.

1. *Heaving of the Ground.*—The peculiar motion felt during an earthquake results from a combination of two kinds of movements; an upward shock or jerk, and a progressive wave or rolling movement, and it is this combination which produces such destructive results. The upward shock opens the cracks and joints in all rocks as well as in the walls of buildings, and the undulating movement rocks them to and fro, shaking down buildings and hurling large masses from sea-cliffs and valley-sides.

2. *Damming up of Rivers.*—The masses of earth and rock thus detached from the sides of a valley often block up the stream at the bottom, and cause the formation of a lake. If the barrier remain, and the stream is diverted into a new course, the lake may be permanent; but if the dam gives way and the pent-up waters escape, the lake is drained and destructive floods are caused.

3. *Opening of Cracks and Fissures.*—Instances of such fissures have been mentioned. They sometimes open and shut again rapidly as the undulating movement passes on, but frequently remain as open clefts or chasms, varying in length from a few feet to as many miles. Sometimes one side of the rent is at a higher level than the other, such a dislocation forming a fault in the rocks below. Rivers are

occasionally engulfed in these fissures, and pursue an underground course for some distance.

3. *Permanent Changes of Level.*—These are the most important geological results which earthquakes produce, for, as already stated, the solid land is sometimes raised or lowered several feet at a time over large areas. The extent of such movements is best seen along the sea-shore, where in the one case a new strip of land may be added to the coast-line by the elevation of the beach and adjacent sea-bottom, or in the other case, if depression has taken place, the sea may have overflowed its ancient limits and encroached upon the land. Inland the slope of water-courses is often altered, the rapidity of the current being increased or diminished according to circumstances, and sometimes rivers are diverted from their former channels. An instance of this in South America is mentioned by Dr. Darwin, on the authority of a resident engineer.

"Travelling from Casma to Huaraz (not very distant from Lima), Mr. Gill found a plain covered with ruins and marks of ancient cultivation, but now quite barren. Near it was the dry course of a considerable river, whence the water for irrigation had formerly been conducted. There was nothing in the appearance of the water-course to indicate that the river had not flowed there a few years previously; in some parts, beds of sand and gravel were spread out; in others, the solid rock had been worn into a broad channel, which in one spot was about 40 yards in breadth, and 8 feet deep. It is self-evident that a person following up the course of a stream, will always ascend at a greater or less inclination; Mr. Gill, therefore, was much astonished, when walking up the bed of this ancient river, to find himself suddenly going down hill. He imagined that the downward slope had a fall of about 40 or 50 feet perpendicular. We here have unequivocal evidence that a ridge had been uplifted right across the old bed of a stream.

"From the moment the river-course was thus arched, the water must necessarily have been thrown back and a new channel formed. From that moment also, the neighbouring plain must have lost its fertilizing stream, and become a desert."[1]

[1] "Voyage of the Beagle," edition 1860, p. 359.

CHAPTER IV.

ELEVATION AND DEPRESSION OF LAND.

WE have already seen that movements of elevation and depression often take place during earthquakes, and that large tracts of the earth's crust have been permanently raised or lowered in this way. We have now to learn that in some parts of the world, where no great earthquakes have happened during the periods of history, there have, nevertheless, been similar changes in the level of the land, the movements taking place quite gradually and imperceptibly, not by jumps and starts as in the case of earthquakes.

There is also reason to believe that both kinds of movement may take place at different times in the same area, slow and imperceptible changes occurring in the intervals between the sudden shocks; there is proof, moreover, that intervals of rest alternate with epochs of movement, and that sometimes movements of elevation have alternated with movements of depression in the same area.

The signs and evidences by which we may know that a movement of upheaval or one of subsidence has taken place in a given district are not equally obvious in both cases. When land is lifted up above the sea, it generally brings up with it some proofs of its having once been under water; but when a coast-line is sinking below the sea-level, the fact is less easily proved, because the subsidence soon removes its surface from our inspection. There are, however, facts of various kinds which are accepted as sufficient evidence of subsidence, and others which are proofs that elevation has taken place. It will be useful, therefore, if we tabulate the indications which can be adduced as evidence for such changes of level, and exemplify each kind of testimony by appropriate instances.

Proofs of Elevation.

1. *Testimony of Human Erections.*—When ancient moles and harbour works have been raised above the level of the sea, they afford very convincing proofs of upheaval, but it is only in countries where man has resided for many centuries that such testimony can be looked for. The island of Crete or Candia is, however, a case in point. This island is about 135 miles long, and Captain Spratt, R.N., ascertained that its western end has been uplifted 17 feet above its ancient level, while a part of the southern coast has risen more than 27 feet, so that the docks of the ancient Greek ports are now above water, as well as masses of limestone rock drilled by *lithodomi*. At the same time, the eastern part of the island has sunk many feet, causing the submergence of several Greek towns, the ruins of which are still visible under the water.

2. *Testimony of raised Rocks and Islands.*—The coasts of Norway and Sweden consist chiefly of hard rocks, and are fringed with numerous islets; and as there are no tides in the Baltic Sea, conditions are there peculiarly favourable for making exact observations on the relative level of land and sea.

South of Stockholm no rise is perceptible, and it appears that there has even been depression, but north of that city the elevation is sufficiently obvious. It was observed early in the last century by Celsius, who remarks that "several rocks on the shores of the Baltic which are now above water (A.D. 1730), were not long before sunken rocks, and dangerous to navigators; one especially, which in the year 1680 was on a level with the surface of the water, is $20\frac{1}{2}$ Swedish metres above it (60 English feet). From an inscription near Aspo, in the Lake Melar, which communicates with the Baltic, engraved, as it is supposed, above 500 years ago, the land appears to have risen no less than 13 Swedish feet (12·66 British)."[1]

Celsius' statements excited so much attention and discussion, that lines or grooves, together with the date of the

[1] "Playfair's "Illustrations of the Huttonian Theory," edition 1822, p. 436.

year, were cut in the rocks at different places along the Baltic to indicate the ordinary level of the water on a calm day. In 1820-21 all these marks were examined by the officers of the pilot establishment of Sweden, and they reported that the level of the Baltic was certainly lower, relatively to the land, than it had been, but that the amount of change had not been everywhere the same. During their survey they also cut new marks for the guidance of future observers.

Sir Charles Lyell visited Sweden in 1834, with the view of determining this question, and specially examined the marks cut on the shores of the Gulf of Bothnia. He found that the level of the sea at that time was several inches below the marks cut by the pilots, and from 2 to 3 feet below the more ancient marks. Thus at Gefle, north of Stockholm, for example, he found that the land had risen about 4 inches in the interval between 1820 and 1834, and, consequently, that the upward movement had proceeded at the rate of about $2\frac{1}{2}$ feet in a century. He ascertained also that the testimony of the inhabitants, both on the eastern coasts and on the western near Gothenburg, agreed with that of their ancestors—viz., that the low rocks, both on the shore of the mainland and on the islands, are more and more exposed to view.[1]

3. *Testimony of Marine Shells.*—The evidence already cited refers only to recent historic times, but there are other and convincing proofs that the elevation of Scandinavia has been going on for many centuries, and that similar upward movements have taken place in many other parts of the world. The first of these proofs is the existence of beds of sea-shells, sometimes many miles in the interior of the country, and often at a height of several hundred feet above the present level of the sea.

In Sweden, for example, such banks containing recent marine shells have been met with at many localities, and at various heights, from 10 to 200 feet. Between Stockholm and Gefle there are deposits containing shells of the same species as now inhabit the brackish waters of the Bothnia Gulf up to elevations of 100 feet. Lyell traced

[1] "Principles of Geology," tenth edition, vol. ii. p. 190-1.

these beds inland to a point on the southern shores of Lake Maeler, about 70 miles from the sea; and M. Erdman has subsequently traced them to Linde, a distance of 130 miles from the sea, where they occur at a height of 230 feet.

Similar beds of sea-shells have also been found at an elevation of 200 feet on the northern border of Lake Wener, 50 miles from the western coast, so that a very large area must have been added to Sweden in comparatively recent times.

Uddevalla, near Wenersburg, is another place where beds of recent shells have been found; and here M. Alex. Brongniart, on removing part of the shell deposit, perceived that the underlying surface was covered with barnacles still firmly adhering to the rocks. This observation was verified by Sir C. Lyell by a similar discovery at another spot near Uddevalla.[1]

In parts of Norway deposits containing sea-shells of recent species occur at elevations of 600 and even 700 feet, according to Mr. Torell.

Dr. Darwin has described the beds of sea-shells which he found at various heights above the sea along the west coast of South America. Commencing at Tierra del Fuego, he traced them for a distance of 2,075 miles along the western coast, and at various elevations, from 300 to 1,300 feet above the sea. They occur in connection with the raised beaches presently to be mentioned; and Darwin remarks that the shells at the lower levels were fresh, but that those at the greater heights were brittle and decomposed from prolonged exposure to the weather. Those near Valparaiso, where he found them up to a height of 1,300 feet, were embedded in a reddish mould, having a guano-like smell, and in which minute fragments of sea-urchins and other marine animals could be detected.

4. *Testimony of Raised Beaches.*—A beach may be defined as an accumulation of sand or shingle piled up by the action of the waves against a shore line. Wherever the shore is backed by a range of cliffs a beach is formed along their base. If the land is elevated, both beach and cliff-line are lifted above the reach of the waves, a new beach is formed

[1] "Principles," vol. ii. p. 192.

at a lower level, and the old beach remains as a gently sloping shelf or terrace between the cliffs and the sea margin (see fig. 11).

The width of this terrace will depend on the slope of the shore, and the length of time during which the land re-

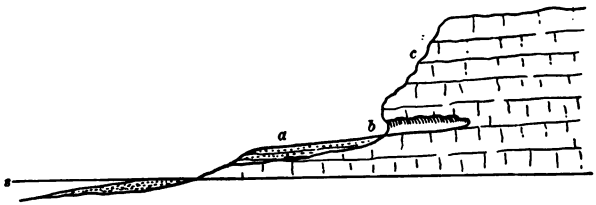

Fig. 11.

a, raised beach. *c*, cliff.
b, cave. *s s*, high-water mark.

mained stationary. Sometimes a succession of narrow benches or terraces may be traced round lofty cliffs, one above another, indicating successive pauses between the movements of upheaval by which the land was elevated to its present height.

Scandinavia.—Such raised beaches and ancient sea-margins form conspicuous features in some parts of Norway and Sweden. The rise seems to have been greater towards the east as well as towards the north, the whole country being tilted up in a north-easterly direction. On the south-west coast of Norway the smooth, rounded rocks slope gently under the sea, and no signs of upheaval are to be seen; but eastward, along the sides of the long fiords which run into the land, notches in the rocks and low terraces become visible; and, at the east end of the Sogne Fiord, these rise to a height of 300 feet above the sea. Northward along the coast no signs of upheaval are met with till the district of Drontheim is reached, where a long low flat intervenes between the shore and the cliffs. Beyond this point every fiord and valley has beautiful terraces along its sides, rising northward and eastward to levels of 200 and even 500 feet above the sea. In Finmark, along the Altenfiord, there are terraces at successive levels of

56, 65, and 143 feet; but the uppermost does not maintain a constant level, for, in a distance of 48 miles, one end of it was found to be 58 feet below, and the other end 96 feet above the normal line, the north end being thus 154 feet higher than the other. Here, therefore, the elevation during the formation of this terrace was very unequal.

South America.—The repeated elevations which have taken place along the west coast of South America during earthquakes have been mentioned in Chap. III. But Dr. Darwin obtained evidence that, besides these sudden paroxysmal movements, there had been a slow and imperceptible rise of the land, and that the elevation had probably been greater inland than on the coast. Raised beaches occur along both sides of the continent, and form a succession of terraces, which are in some places very conspicuous. Thus, "at Coquimbo, five narrow, gently-sloping, fringe-like terraces rise one behind the other, and, where best developed, are formed by shingle. They front the bay, and sweep up both sides of the valley. At Guasco, north of Coquimbo, the phenomenon is displayed on a much grander scale, so as to strike with surprise even some of the inhabitants. The terraces are there much broader, and may be called plains. In some parts there are six of them, but generally only five: they run up the valley for thirty-seven miles from the coast."[1]

England.—Raised beaches have been found at several places along the southern and western coasts—as, for instance, in Cornwall,[2] at Portland,[3] and Brighton. The following account of the Brighton beach is taken from Mantell's "Medals of Creation;" the illustration (fig. 12) represents the appearance of the cliffs east of Kemptown in 1836, and fig. 13 shows the arrangement of the beds forming the cliffs, as actually seen in a ravine between Kemptown and Rottingdean.

At the base of the cliffs, and bounding the modern beach,

[1] "Voyage of the Beagle," Darwin, 1860, p. 343. Many of these beaches contain sea-shells, as already mentioned, p. 52.

[2] See De la Beche, "Geology of Devon and Cornwall," and Ussher, "Geol. Mag.," 1879, p. 166.

[3] See Prestwich, "Quart. Journ. Geol. Soc.," xxviii. p. 38; xxxi. p. 29.

there is a low wall or terrace of chalk, and upon this rests a bed of sand (*o*, in fig. 13), of irregular thickness and

Fig. 12. Brighton Cliffs, near Kemptown, looking east.
a, the Elephant bed. *b*, shingle beach.
c, the underlying chalk.

variable extent. From this sand marine shells and the jaw of a whale have been obtained. Upon this sand is a bed of loose shingle similar to that of the present beach, though

Fig. 13. Section through the Brighton Cliffs.
a, Elephant bed. *o*, bed of sand.
b, ancient shingle. *c c*, chalk.

the pebbles of which it consists are not all flints. In this ancient shingle the teeth and bones of various extinct animals have been discovered.

The rest of the cliff above the shingle bed consists of a mass of chalk rubble and loam, obscurely stratified, and varying in thickness from 50 to 120 feet. This deposit was named the "Elephant bed" by Dr. Mantell, on account of its containing so many teeth and bones of the extinct elephant, known as the mammoth, together with the remains of other animals, such as the rhinoceros, horse, deer, and oxen. Still more extensive beds of shingle, overlaid by loam, occur on the western side of Brighton, and stretch inland for several hundred yards from the shore.

These facts demonstrate the following series of changes in the relative level of land and sea:—

1. The chalk terrace on which the sand and shingle rest was at the sea-level for a long period, and a beach was formed at the base of the chalk cliffs then existing.

2. The whole line of coast was submerged to such a depth as to admit of the deposition of the overlying deposit (*a*).

3. The land was elevated to its present level, and the formation of the present beach and line of cliffs was commenced; the latter have been cut back to their present position by the action of the waves, which will be described in a future chapter.

Scotland.—Well-marked terraces with raised beaches have been traced at intervals along the Scottish coasts, four or five sometimes occurring one above the other, at heights of 25, 40, 60, 75, and 100 feet above the present high-water mark.[1]

5. *Testimony of Old Sea-Caves.*—The formation of caves by the action of the sea-waves beating against a line of cliffs will be described in a future chapter. The caves are excavated at the foot of the cliffs, and consequently, if the coast is afterwards elevated, these caves will remain as evidence of the level at which the land formerly stood. Excellent examples of such old cliffs and caves occur at various heights along the rocky coasts of Scotland up to a

[1] See Geikie's "Scenery and Geology of Scotland."

level of 100 feet above the sea, and are often associated with the raised beaches (as in fig. 11).

The lowest of these beaches is very marked along the coast of Cantyre, and is thus described by Professor Hull:[1] —"All along the coast the ancient sea-margin may be traced by a line of cliffs of various degrees of steepness according to the nature of the rock. . . . From the base of this cliff a slightly shelving terrace extends to the present sea-margin, on which most of the villages are built. The surface of this terrace is often diversified by rocks, sometimes rising in isolated and fantastic masses above the level surface of the terrace and resembling in form and features those at a lower level, which are now subject to the full play of the breakers. . . . The caves which are found at intervals all round the coast, and which form a range of natural rock-hewn compartments at a level of 10 to 30 feet above the present tidal limits, are perhaps the most convincing of all the various evidences of ancient sea-action." Some of these caves near Campbelton and Neill are specially described, and extend into the cliff for a distance of 120 feet.

Proofs of Depression.

It has already been remarked that the proofs of the submergence of land are not generally so obvious as those of its elevation; so that to a careless observer elevation will appear to have been more general than depression in most parts of the earth. In some cases, however, there is direct evidence in the actual submergence of buildings and former land-surfaces; and in other cases the fact of depression can be as certainly deduced from certain observations which will be better understood when the student has read the information given in Chapters VII. and XI. We shall, however, endeavour to state the evidence and explain the reasoning as simply as possible in the present connection, recurring again to the subject on a future page.

1. *Testimony of Human Erections.*—Where the land

[1] "Geol. Mag.," vol. iii. p. 6.

has been sinking for a long time, the ruins of ancient towns and buildings are sometimes visible beneath the sea; as, for instance, at the east end of Candia, mentioned on p. 50. It is necessary, however, to point out that the mere encroachment of the sea upon the land cannot be accepted as proof of subsidence, because, as will be explained in a future chapter, the waves can cut back a coast line, and cause the successive disappearance of fields, houses, and villages, without being aided by any movement of depression. It is requisite, therefore, that the relation of the buildings to the sea should be such as to demonstrate that an actual change of level has taken place.

This is the case on the western coast of Greenland, which was surveyed by Captain Graah and Dr. Pingel between the years 1823 and 1832. They arrived at the conclusion that the land had been sinking for the last four centuries between Igaliko, in 60° 43′ N. lat., and Disco in 69°, a space of 600 miles. "Ancient buildings on low rocky islands have been gradually submerged, and experience has taught the aboriginal Greenlander never to build his hut near the water's edge. In one case the Moravian settlers have been obliged more than once to move inland the poles upon which their large boats were set, and the old poles still remain beneath the water as silent witnesses of the change."[1] Again, in Scania, the most southerly part of Sweden, there is similar evidence that the land is sinking. In many of the seaport towns some of the streets are below the level of high-water mark, and ancient streets have been found at a still lower level. Thus, at Malmö, one of the present streets is overflowed by the waters of the Baltic when the wind is high, and excavations made some years ago disclosed an ancient street at a depth of 8 feet below the present one. There is a large stone at Trelleborg, the distance between which and the sea-margin was measured by Linnæus in 1749, and in 1836 it was found to be 100 feet nearer the water's edge than it was eighty-seven years before.

3. *Testimony of Submerged Forests.*—When a tract of land is depressed beneath the sea, its superficial layer is

[1] Lyell, "Principles of Geology," ii. p. 196.

generally removed by the action of the waves; but under favourable circumstances, in sheltered bays and estuaries, or by the formation of sand dunes, the old terrestrial surface is sometimes preserved, and the stumps of old trees are often seen on the shore at and below present low-water mark. De la Beche thus describes the remains of such an old land surface exposed along the south-west coast of England.[1] "Round the shores of Devon, Cornwall, and West Somerset, a vegetable accumulation, consisting of plants of the same species as those which now grow freely on the adjoining land, is frequently discovered, occurring as a bed at the mouths of valleys, at the bottoms of sheltered bays, and in front of and under low tracts of land, the seaward side of which dips beneath the present level of the sea."

Similar beds of peaty matter occur at numerous points all round the coasts of Great Britain and Ireland, proving that the last movement to which these islands have been subjected, was one of depression. Two instances may be adduced:—

1. In the harbour of Holyhead a bed of peat 3 feet thick, with the stumps and roots of trees, is exposed at low water, and stretches upward to a slight elevation above the sea, where the excavations made for the railway in 1849, showed that it was covered by stiff blue clay, and brought to light two perfect heads of the extinct elephant known as the mammoth.

2. A submerged forest of large extent exists off the north coast of Norfolk from Hunstanton to Brancaster Bay. The portion exposed at low-water, north of Hunstanton cliff end, is about a mile and a half from high-water mark, and consists of a thick bed of black peaty matter, composed of small twigs, branches, leaves, and other vegetable remains matted together, and enclosing the trunks, stumps, and roots of large timber trees. The forest here occupies an area of at least 500 or 600 acres, and among the roots are occasionally found the remains of deer and oxen, proving that these animals once roamed through the forest. Possibly also they may have been hunted here by the early

[1] "Geological Report on Devon and Cornwall," p. 420.

inhabitants of Britain, for a flint-celt or axe was found embedded by its cutting-edge for a depth of an inch and a half in the trunk of one of the trees. A similar forest-bed is found along parts of the Lincolnshire coast, and is overlaid by the recent clays of the marshland.[1]

3. *Testimony of Buried Valleys.*—That rivers make their own valleys will be proved in a subsequent chapter, but accepting the statement for the present, it is evident that so long as the country remains stationary, no river can excavate its channel lower than the low tide level of the sea into which it flows. On the east coast of England, however, there are many river valleys, the rocky bottoms of which are 40 or 50 feet below low-water mark, being filled up to that level with deposits of gravel, sand, and silt. For instance, the rivers Yare and Waveney, in Norfolk, flow through flat alluvial tracts for many miles before they reach the sea, the width of the valleys being great in proportion to their apparent depth; though the real depth of the original valley is in accordance with this width. In the valley of the Yare, at Wroxham Bridge, there is as much as 70 feet of detrital matter between the present alluvial level and the chalk which forms the bottom of the actual valley.

Borings at the mouth of the river Tees prove that the bottom of the ancient valley is about 200 feet below

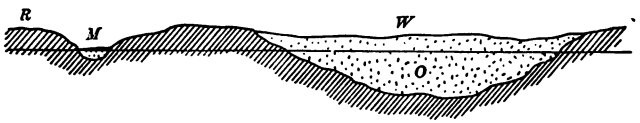

Fig. 14. The buried Valley of the Mersey.
Hor. scale, 2 inches to a mile. M, present valley; O, ancient valley filled with drift; W, site of Widnes; R, site of Runcorn.

Ordnance datum, or mean sea-level; and a boring near the mouth of the Tyne was carried to a depth of 124 feet without reaching the rock-bed of the valley.

Again, borings at Widnes, on the north side of the

[1] For other examples of submerged forests, see "Geol. Mag.," vol. vii. p. 164, and Dec. 2, vol. iii. p. 491. "Quart. Journ. Geol. Soc.," xxxiv. p. 447.

estuary of the Mersey, have shown that there is a buried valley nearly a mile in breadth and with an extreme depth of 163 feet from the present surface, and 141 feet below Ordnance datum. Fig. 14, which is copied from that drawn by Mr. Mellard Reade, shows the comparative size of the present and the ancient valley of the Mersey between Runcorn and Widnes.

The natural conclusion from such cases is that, when the rivers excavated their valleys to the depth thus ascertained, the land stood at a higher level, and the bottom of the valley was at or above the level of low-water mark; that the whole country must have been subsequently depressed beneath the sea, and the old valley filled with marine deposits; and that the land has never again been elevated to the height at which it stood when that valley was excavated.

Similar old valleys and river channels have been discovered in Scotland, so completely buried by subsequent deposits that there is no indication of their presence on the surface; in some cases the sites of these buried valleys are covered by low hills or mounds more than 100 feet high, so that the courses of the ancient rivers must have had very different directions from the present streams.

One of these old river channels has been traced from Kilsith in Stirlingshire to Grangemouth on the Firth of Forth. The surface of the ground at Kilsith is now 160 feet above the sea, and the old valley bottom lies at a depth of 120 feet, or 40 feet above the sea; thence it slopes gradually eastward till at Grangemouth the old channel is 260 feet below the sea level.[1]

At the time, therefore, when this channel was occupied by the river which made it, the land must have been at least 260 feet higher out of the sea than it is now, an elevation which would be sufficient to unite the British islands to the continent of Europe.

4. *Testimony of Fiords.*—A fiord is a long narrow inlet of the sea which does not terminate abruptly, but is the continuation of an inland glen or valley. It is, in fact, part of a depressed valley which is filled with sea-water instead of being choked up with sand and mud, as in the case

[1] J. Croll, "Trans. Geol. Soc. Edin.," vol. i. p. 330.

of the English valleys. The term fiord is a Norwegian name for such narrow inlets, and is the same as our *firth;* it is the multitude of these firths or fiords which cause the outline of the Scottish and Norwegian coasts to present such a peculiarly irregular and indented appearance. All the larger glens and valleys of western Scotland terminate in fiords, or lochs as they are there called, which are simply the submerged prolongations of the glens, and their existence is a proof that the whole country has once stood at a higher level than it does now. In the same way the fiords of the Norway coast prove that a depression took place before the present rise of the country, and that the land has not yet been re-elevated to the level at which it previously stood, when these ancient valleys were first excavated.

5. *Testimony of Coral-Reefs.*—The gradual formation of coral-reefs will be described in a future chapter; the special fact to be observed in the present connection being that the coral-animals only live in shallow water down to a depth of about 15 fathoms. Every reef, therefore, must have originated in water of such a depth, and must have formed a fringe round some island or along a line of coast as in fig. 15. Now suppose this land with its fringing reefs to subside vertically, but so slowly and gradually as not to exceed the upward growth of the coral, it is obvious that the depth of the water over the living surface of the reef would never be materially greater, whatever might be the depth ultimately attained by the rocky base on which the corals first commenced to grow. The height of the reef at its outer edge might be indefinitely increased, and the width to which the inner parts of the reef were extended over the sinking land would be correspondingly increased according as the slope of its shores was gentle or steep.

The original fringing reef then comes to be what is called a Barrier reef, lying at some distance from the land, and rising on its outer side from a great depth of water, while between it and the shore there is a wide lagoon or channel. If the land be an island this barrier reef will surround it, and if the depression be continued till the solid rock is entirely submerged, while the coral rock grows vertically upward, the ultimate result will be an irregular ring-shaped

reef surrounding a lagoon or space of water. Such a coral island is called an Atoll.

The upward growth of a coral-reef over a sinking island is illustrated in fig. 15, the horizontal lines, s^1, s^2, s^3 representing the sea-level at different periods, and indicating the amount of successive subsidences. When the sea was at the level s^1, the mass of the island was above water and the fringing reefs, F F, were formed round its shores. Continual, but gradual, subsidence carried the land downward while the reefs have grown nearly vertically upward, until the sea-level came to coincide with the line s^2. By this submergence the limits of the land would be much contracted, and the distance between its shores and the encircling reefs would be correspondingly increased, so that

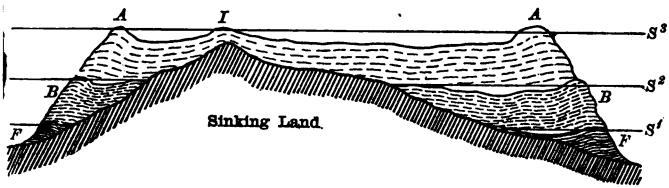

Fig. 15. Conversion of a Fringing Reef into an Atoll.

the latter were eventually converted into barrier reefs, B, B. At the stage s^2, these reefs lay at a considerable distance from the coast of the sinking island, and were separated from it by a wide lagoon.

If the subsidence still continued, the width of this lagoon would still further increase, and every part of the land would be covered with a growth of coral, until the whole was converted into an Atoll, A, A, or ring of reefs without a central island; except, perhaps, an inner reef raised upon the last disappearing point of land, as at I.

Some Atolls, however, may have been formed upon the summits of submarine volcanoes, and are not, therefore, such certain proofs of depression having taken place; but barrier reefs, partially or wholly surrounding large islands, or fronting a continental coast line such as that of N.E. Australia, may be taken as unquestionable evidence of depression.

The great Australian barrier reef is about 1,250 statute miles in length, from 10 to 90 miles in width, and rises at its seaward edge from depths which in some places exceed 1,800 feet. Mr. Jukes [1] compares it "to a great submarine wall or terrace, fronting the whole north-east coast of Australia, resting at each end on shallow water, but rising from very great depths about the centre; its upper surface forming a plateau covered by 10 to 30 fathoms of water, but studded all over with steep-sided block-like masses which rise up to low-water level. These masses are especially numerous and most linear along the edge of the great bank on which they rest, the passages between them being often very narrow, like regular embrasures opened here and there through the parapet wall of a fortress. These 'individual reefs' running along the outer edge protect the comparatively shallow water inside, and with the numerous inner reefs that are scattered over its space make it one great natural harbour."

General Conclusion.—Combining all the evidence which has been presented to the reader in this and the preceding chapter, we arrive at the conclusion that the earth's crust, instead of being a rigid, immovable mass, as was formerly supposed, is, and always has been, utterly unstable. It is probable, indeed, that no part of the land remains stationary for any long period of time, geologically speaking; but is eventually either slowly depressed, or as slowly upraised to a still higher elevation above the sea. It is certain, at any rate, that the form of the great continents has been continually altered, parts being elevated, and parts depressed, so that every portion has in its turn been brought beneath the level of the sea. It is certain, also, that every country is now dry land only because it has been upraised from beneath the neighbouring sea. This great truth will be still further demonstrated in subsequent chapters.

[1] "Manual of Geology," second edition, p. 131. See also "Voyage of H.M.S. Fly," vol. i. ch. xiii.

SECTION II.—Changes produced by the Influence of Subaerial or Surface Agencies.

A. *Processes of Disintegration.*

CHAPTER V.

TERRESTRIAL AGENCIES.

IN the preceding chapters we have considered the general movements which take place from time to time in the crust of the earth, these movements probably being due to certain physical operations which tend to disturb the equilibrium of the earth's crust, and to cause displacements of the matter composing the liquid substratum which underlies it. We are not yet in a position to discuss the precise nature of these disturbing causes, but we have seen that the general result of the forces at work is to produce movement in one of two directions—either elevation, or depression; that some portions of the earth's surface are being slowly elevated, and others are being slowly depressed, with occasionally more rapid movements in one or the other direction.

Now, when any portion of the earth's crust has been thus raised above the level of the sea, it is at once exposed to the conditions which result from the existence of the atmosphere surrounding our globe. It is assumed that the student has read some elementary work on Physical Geography, thereby acquiring some knowledge of the nature of these atmospheric conditions and being prepared to follow more detailed descriptions of the important effects which heat and cold, rain and frost, running water and moving ice, produce upon all surfaces exposed to their action. Some of these agents are chiefly engaged in breaking up

and wearing down the rock-masses, others are more concerned in transporting and re-arranging the detritus, but the ultimate result to which all contribute is the re-construction of these materials and their deposition as new formations in the beds of rivers, lakes, and seas.

In considering the operations of these agencies, therefore, it will be desirable to arrange our descriptions in two sections, confining our attention in the first part to their destructive and dispersive effects, and leaving to the second section the consideration of what may be termed their collective and reconstructive effects.

Before entering further into the subject, however, it is necessary to explain some of the technical terms which are used by geologists in describing these processes. The term *Denudation* is usually applied to the destructive effects of these agents, and it is used in all geological manuals to signify the removal of material from the surface of the land. The author has long felt dissatisfied with this use of the term denudation, because it is an absolute perversion of its proper and original meaning. *To denude* (Latin *denudare*), is to uncover or lay bare a surface, and though such denudation necessarily involves the removal of matter, it is not this matter, but the underlying surface which is denuded; consequently it is incorrect to speak of denudation in the sense of wearing away and removing material without reference to the uncovering of any particular stratum. *Degradation* has sometimes been used in this general sense, but it is open to the objection that it has already acquired a different meaning in the English language. *Detrition* (from *detero*, to wear down), has not hitherto been used as a technical term in geology, though the words *detritus* and *detrital* are frequently employed, and *attrition* is a common English word. The word *detrition*, therefore, is not a great innovation, and in proposing it as a general term to express the result of the processes concerned in producing detritus, and in removing material from the surface of a country, I hope for the support of all geologists who appreciate the value of precise language.

We may then frame the following definitions:—

1. *Detrition* is the removal of rock-material from the land.

2. *Denudation* is the laying bare of rock-surfaces by the detrition of the overlying beds.

3. *Erosion* is the localized action of any detritive agent.

4. *Deposition* is the disposal of the detritus worn from the denuded surface.

Consequently we shall be correct in speaking of

The detrition of a district.
The erosion of valleys.
The denudation of fresh rock-surfaces.
The transportation and deposition of detritus.

The subject matter of the present section may be thus arranged:—

	Agents.	Action.
I. Terrestrial Agencies.	Surface agents . .	Chemical and Mechanical.
	Percolating waters .	
II. Fluviatile Agencies.	Rivers	Chiefly Mechanical.
	Glaciers	
III. Marine Agencies.	Tides and Waves . .	Mechanical.
	Coast-ice	

I. Terrestrial Agencies.

It is common matter of observation that all rock-surfaces which have been exposed to the action of the weather for any length of time show a tendency to decay and crumble away. The agencies concerned in producing this *weathering*, or disintegration, are several; they act both chemically and mechanically, but they are all so intimately connected in their operations, that any given case of disintegration can generally be shown to be the result of the conjoined action of two or more of them.

They may, however, be arranged as follows, and we shall endeavour, as far as possible, to consider their separate effects.

	Agents.	Mode of action.
Superficial.	Rain	Chemical and Mechanical.
	Wind	Mechanical.
	Heat and Cold. .	Mechanical.
	Frost	Mechanical.
Underground = Percolating water		Chemical and Mechanical.

Rain.—All the rain which falls upon the surface of the land is disposed of in one of three ways: 1. Some of it is immediately returned again to the atmosphere by evaporation. 2. Some of it trickles down slopes, and collects into rills and streams, which flow over the surface of the land. 3. Some of it sinks into the ground, and percolates through cracks and joints of the rocks. The rain-water which flows over the surface operates as a mechanical agent, and carries off with it particles of the soil or rock over which it passes in *mechanical suspension*. The rain-water which sinks into the ground acts chemically, it dissolves certain portions of the rocks, through which it percolates, and carries them away in *chemical solution*.

Some of this percolating water is thrown out again to the surface in the form of springs, but the remainder penetrates still further into the substance of the earth, where, with the aid of heat and pressure, it effects great changes in the chemical constitution of the more deeply-seated rocks, and is largely concerned in producing the phenomena of hot springs.

The Chemical Action of Rain.—Before proceeding to describe the chemical effects of rain-water on the earth, a few words of explanation are necessary, in order that the source of its chemical energy may be properly understood. Pure rain-water would have little effect upon any rock-substance except common salt; its rotting and dissolving powers are mainly due to its capacity for taking up and absorbing a certain gas called carbonic acid or carbonic dioxide ($C O_2$), but partly also to the presence of free oxygen. Carbonic acid gas exists everywhere in the atmosphere surrounding the earth, though the quantity contained in the air at different places varies considerably. All animals exhale carbonic acid from their respiratory organs, and all living plants decompose carbonic acid, absorbing the carbon and setting free the oxygen; but when they die and decay, a process of oxidation goes on, and carbonic acid is again formed. Both living animals, therefore, and decaying vegetables produce carbonic acid, and increase the proportion of this gas in the air around them.

Carbonic acid is readily absorbed or dissolved by water;

and, as a matter of fact, all water on the earth's surface contains a greater or less amount of this gas. Rain takes up some from the air through which it falls, and obtains still more from the soil through which it percolates. Water thus charged with carbonic acid is often called carbonated water, and it exercises a powerful disintegrating action on the rocks into which it soaks. Some of their constituents are chemically attacked, and carried away in solution; other particles become loosened in the process, and are eventually removed by the mechanical action of the rain-streams.

This gradual decay and disintegration goes on wherever the surface of a rock is kept continually wet with rain and moisture. Plants increase the chemical action by enabling the moisture to lodge and remain for a longer time on the spot, but they retard the mechanical action, and prevent the loosened particles from being carried away, so that these accumulate and form a soil.

The substances soluble in carbonated water are:—

More soluble.	Chlorides. Carbonates. Sulphates. Nitrates.	Less soluble.	Most Oxides. Silicates of the alkalies.[1]

The less soluble substances are, however, more soluble in water which has already dissolved alkaline compounds; thus, if rain water in soaking through rocks near the surface takes up much carbonate of sodium or potassium, it is able to dissolve more of any alkaline silicates it may meet with in its further course through the rocks below. Moreover, if the action of the alkaline solution is aided by that of a high temperature, as is often the case in volcanic districts, large quantities of silica or of silicate may be dissolved in the warm alkaline water.

But, besides carbonic acid, all natural waters contain another active agent in the shape of oxygen gas. This readily combines with metals, and with all oxides which can absorb more oxygen, and by this *oxidation* different mineral compounds are formed. The rusting of an iron nail is a familiar example of this action, and, similarly,

[1] The commonest alkalies are sodium and potassium.

any protosalt of iron which may occur in a rock will be oxidized, and a rusty brown colour will generally be imparted to the decomposed and disintegrated mass.

The Action of Rain on Calcareous Rocks.[1]—Carbonate of lime enters into the composition of many rocks; some, indeed, such as chalk and other limestones, being almost entirely composed of it. Since the material of such rocks is readily soluble in carbonated water, it is evident that they will show signs of rapid decay and disintegration. A limestone which is nearly pure carbonate of lime, is so completely dissolved that little remains to form a soil, and that little is quickly swept off the surface by rain, so that districts composed of such limestone are usually bare and barren. Limestones which contain an admixture of sand or siliceous matter are converted into the substance known as *rottenstone;* the calcareous portion being eaten out and carried away in solution, while the insoluble particles are left to form a rotten and friable rock.

Impure limestones containing argillaceous (or clayey) matter are similarly disintegrated, the insoluble residue remaining, and crumbling down to form a soil. Such a residual soil, therefore, gives us a rough measure of the amount of rock removed by solution.

By the double process of dissolution and oxidation, calcareous sandstones are often reduced to the condition of a loose brown sand, or friable sandstone. Sands that were originally full of calcareous shells are frequently converted into a ferruginous sand, entirely devoid of organic remains. Thus, in the east of England there are certain shelly sands, called *crag*, the surface beds of which have been so altered

[1] In this and the following chapters it is assumed that the student has read some more elementary works on physical geography and geology, such as Geikie's Primers, Sharpe's "Rudiments," or Jukes's "School Manual of Geology." It is, therefore, taken for granted that he is acquainted with the chemical composition and general characters of the commoner minerals and rocks; that he knows the difference between quartz and felspar, and that he has handled specimens of chalk, flint, sandstone, limestone, granite, gneiss, and basalt. If, however, the reader happens to be without this knowledge, he should carefully peruse the first four chapters of Part II. before proceeding further in this part of the subject.

by this process that they were long believed to be a distinct formation.[1] The line of separation between the altered and unaltered portions is always clearly defined, but very irregular, because the depth of the former varies much according to local conditions.

The same phenomena have been observed in Belgium, where calcareous sands have been decalcified and oxidized to a large extent, and their true relations to the underlying beds were quite misunderstood until this fact was recognized, and the process explained by M. Vanden Broeck.[2]

Those ironstone rocks which consist mainly of carbonate of iron are decomposed in a similar manner. Such ironstone, in its unweathered state, is generally a hard compact rock, of a bluish-gray colour, but when weathered it forms a friable yellowish-brown rock. Carbonate of iron is rapidly decomposed in the presence of free oxygen, hydrated peroxide of iron being formed, and carbonic acid being set free. The latter is, of course, immediately dissolved by the water, and the carbonated liquid then acts upon any other soluble matters which exist in the rock, such as the carbonates of lime and magnesia. After the abstraction of these constituents, the mass is essentially a hydrated sesquioxide of iron, with an admixture of alumina and siliceous matter.[3]

Action of Rain on Felspathic Rocks.—It has been already stated that it is not only the rocks containing *carbonate* of lime, which are weathered and worn away by the action of carbonated water. Those containing minerals composed of the *silicates* of lime, soda, or potash, yield almost as readily. Granite affords an instance of this, for the felspar which it contains consists of the combined silicates of potash and alumina. Rain-water falling upon granite decomposes the felspar, removing the silicate of potash, either in the form of a soluble silicate, or by converting it into a carbonate, but leaving the silicate of alumina and the other constituents (quartz and mica) which are very insoluble.

[1] See Whitaker, "Quart. Journ. Geol. Soc." vol. xxxiii. p. 122.
[2] See "Geol. Mag." ser. 2, vol. viii. p. 279.
[3] See Judd's "Geology of Rutland," Mem. Geol. Survey, p. 134.

By this process the substance of the rock is sometimes so loosened and disintegrated that it can be dug out with a spade. On slopes where the rain-water acts mechanically as well as chemically, the materials of the rock are of course removed as fast as they are loosened, being carried away and deposited elsewhere, partly as clay or kaolin (silicate of alumina) and partly as sand (particles of quartz). The large deposits of kaolin (or china clay) in Cornwall illustrate the enormous destruction of granite which has there taken place. The extent of the chemical action is, however, better demonstrated in districts where the decomposed granite is not carried away so rapidly, but is left as a loose crumbling mass.

A good instance of this is given by Mr. W. Kingsmill in describing the granite of the mountains near Canton in China. He says:—"This granite, wherever it occurs, has been deeply disintegrated, sometimes to a depth of 100 or 200 feet, whilst everywhere, imbedded in the soft, yielding matrix, there occur nodules, of more quartzose character, which have resisted the effects of time and chemical change. The original quartz veins of the granite, broken into small fragments, still traverse the disintegrated mass in all directions."[1]

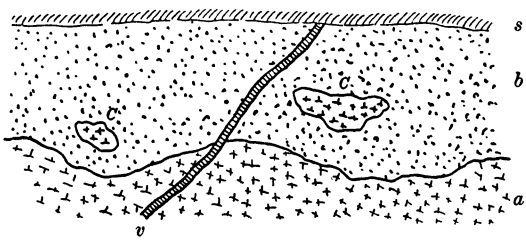

Fig. 16.

v, vein of quartz. *s*, vegetable soil. *c*, core of granite. *b*, decomposed granite. *a*, solid granite.

In Devon and Cornwall granite is often thus decomposed to depths of 30 or 40 feet, and where excavated presents the appearance in fig. 16. The loose sandy part (*b*) is

[1] "Journal of the Geol. Soc. of Dublin," vol. x. p. 2.

shown to be simply the decomposed substance of (*a*) by the detached lumps and cores of undecayed granite (*c*) which are scattered here and there throughout the mass, The veins of quartz, too, which occur in the solid granite, and resist the chemical action of the rain-water, are continued upwards through the disintegrated portion, and prove that the whole originally formed one solid mass of rock. An excellent example of this is to be seen in the Carclaze mine, near St. Austell's, Cornwall.

Almost all igneous rocks contain some kind of felspar, which is acted upon by carbonated water, the silicates of lime, potash, &c., being converted into carbonates, and carried away in solution. The other constituents of volcanic rocks, such as augite and hornblende, contain much iron, and the ultimate result of their decay is a brown ferruginous loamy sand. It is a well-known fact that the soil formed by the decomposition of volcanic rocks is particularly rich and fertile, and that the slopes of Vesuvius, Etna, and other volcanoes, are thickly clothed with forests and vineyards.

Mechanical Effects of Rain.—Everyone is aware that rain exercises a mechanical action in washing off the finer particles of soil, or of chemically disintegrated rock: that all rain falling upon the land and running over its surface carries away a great quantity of such fine material, and that the muddiness of all rills and streams after continuous rain is a clear attestation of this fact. But most people are not fully aware how greatly this action is intensified when the rainfall is very heavy, and when it runs down steep slopes; the effects of a heavy rain-storm in a mountainous district should be witnessed before they can be adequately realized, but it is no exaggeration to say that the rills of rain are capable of moving débris of a size which would constitute gravel. In tropical countries the wearing, excavating, and carrying powers of rain are still greater in proportion to the much greater volume of water which descends in a given time.

In temperate regions this wasting of the surface is more gradual, but it is constantly going on, and though the amount removed from any given area during one year is hardly apparent, yet the course of years renders it appre-

ciable, and cases sometimes occur in which the amount of detrition which has taken place can be actually measured. An excellent illustration of the mechanical effects of rain is furnished by the earth-pillars found in some of the valleys of the Tyrol, and described by Sir Charles Lyell. These are columns of indurated mud or clay, varying in height from 20 to 100 feet, and usually capped by a single stone or boulder. The history of their formation is as follows. The whole valley was once filled with the hard mud or boulder clay, which is of a peculiarly solid and homogeneous nature, weathering with a vertical face like a hard rock, but containing numerous and often very large stones or boulders. Through this material a mountain torrent has excavated a deep channel, leaving two platforms, one on each side of its course. The heat of the sun causes the clay to crack in all directions, and these vertical cracks are gradually widened and deepened by the frequent rains which fall in the valley. The rain-drops gather into rills which course down the steep sides of the ravine, and its banks would moulder away like those of other valleys, were it not for the large stones which occur in the clay; these throw off the rain and protect the clay below from its fretting action, while that around is washed away, so that in time detached columns, or pyramidal pillars are left, each capped by the protecting block which was the initial cause of its development. Sometimes the capping-stone falls off and the column then terminates upward in a point, or becomes separated into several smaller pillars by the weathering out of other blocks within its mass, which in their turn serve as new capping-stones.

The desert country, called "the Bad Lands," in the Washakie Basin, between Utah and Wyoming, U.S., affords another good instance of rapid and extensive erosion by rain. This district is a bare and barren plateau, consisting of soft marls and sands lying in level layers, and terminating towards the south-east in a bold escarpment, which is carved out into numerous blocks, turrets, columns, and citadel-like masses of most peculiar and fantastic forms. The effect is so architectural that from a little distance the scarp-face presents the appearance of a great walled city, with outlying bastions and buttresses. One of the most

remarkable of the detached masses is figured in the frontispiece of the first volume of the "United States Exploration of the Fortieth Parallel." This is an isolated column springing from a level desert plain to a height of fully 60 feet; its lower portion forms a kind of base or pedestal 9 or 10 feet high, above which the pillar narrows slightly, and then rises vertically, till it terminates in a roughly-truncated summit. This massive column looks like a monument erected by the hand of man, and its general shape bears no little resemblance to a lighthouse.

In describing these peculiar forms of erosion, Mr. Clarence King, of the U.S. Survey, gives the following explanation of the way in which they have been produced:[1] "The small streams which cut down across the escarpment from the interior of the plateau do the work of cutting the front into detached blocks; but the final forms of these blocks are probably the effect of rain and wind-storms. The material is so excessively fine that, under the influence of trickling water, it cuts down most easily in vertical lines. A semi-detached block becomes quickly carved into spires and domes, which soon crumble down to the level of the plain. Outlying hills or buttes are carved away, leaving narrow isolated spires, which finally disappear by the same process of erosion. It seems probable that some of the most interesting forms (like the column above described) are brought out by a slightly harder stratum near the top of the cliffs, which acts in a measure as a protector of the softer materials, and prevents them from taking the mound-forms that occur when the beds are of equal hardness."

Good instances of the manner in which some rocks are wasted away by the action of rain have come under the notice of the writer while surveying a part of Lincolnshire, where the ground consists of a soft, loose sandstone, resting on a bed of stiff clay. The sandstone is easily disintegrated by the action of rain and frost, and its surface weathers into a loose sandy soil, the particles of which are readily carried away by the mechanical action of the rain. The borders of this district form sloping ground, trenched

[1] "Exploration of the 40th Parallel," vol. i. p. 399.

by numerous gullies and valleys, worn by the rills into which the rain collects, and cut down near their terminations to the level of the underlying clay. Some tracts are found where the once continuous sheet of the sandstone has been reduced to the condition of low mounds or hills, separated by wide interspaces, over which nothing but a sandy soil remains to cover the surface of the clay. These interspaces are the sites of the hollows or gullies which were worn in the sandstone, and were gradually deepened and widened by the washing away of the sand, until the surface of the underlying clay was bared. The remnants of the sandstone are thus left as disconnected patches; and these remnants are still being reduced by the wasting action of the rain, and are, as it were, gradually melting away under its influence. This process of detrition, therefore, results in the denudation, or laying bare, of an underlying stratum.

Action of Wind.—Where the soil is dry, and loose enough to be moved by the wind, such particles often operate as powerful agents of detrition. Everyone is familiar with the capacity of wind to blow away particles of dust and sand from the surface of our streets; and the erosive power of a strong blast, charged with particles of sand, is illustrated in the effects of the artificial sand-blast, by means of which patterns are engraved upon glass. Natural sand-blasts produce similar effects upon the rocks with which they come in contact; but the results differ considerably, according as the rocks are of a nature to resist or to yield to such mechanical action.

Very hard rocks, like basalt or compact limestone, when exposed to the continual friction of blowing sand, are pitted and polished in a peculiar manner. On the Fifeshire coast, near Burntisland, for example, blocks of basalt can be seen which have been polished in this manner by the sands of the seashore. The author has also observed polished surfaces on the sides and angles of the limestone rocks, near the great pyramid in Egypt; and the same effect has been produced by wind-blown sand on the surface of many Egyptian monuments.

Where, however, the rocks are soft, or their surface has been disintegrated by the rotting action of rain-water, the

results are very different. Such rocks are not polished, but are gradually abraded, and worn away by the friction of the particles driven by the wind. The rapidity of this action depends greatly on the power of the wind, and the size of the particles which it carries; but since the wind cannot raise the larger particles of sand very high above the surface of the ground, it follows that the greatest amount of erosion will take place at, or slightly above, that surface. An isolated block of such a rock as sandstone, if long exposed to sand-drift, will be worn away at the base or undercut, until it presents the appearance of a gigantic mushroom. Some of the celebrated "Brimham rocks," in Yorkshire, exhibit this form very strikingly.

The "tors" and "logging stones," so frequent in granitic districts, probably owe their peculiar form to the combined action of wind and rain. Many of these form piles of rounded or sub-angular blocks, perched one on the other, as if by artificial means; and hence they have sometimes been mistaken for Druidical remains. When examined, however, by the light of geological knowledge, it becomes clear that the apparent ruins are the work of Nature's carving tools—wind, rain, and frost.

In arid climates, the agency of sand and dust-storms is greatly intensified; and Dr. A. Geikie believes that some of the peculiar features of the sandy plateaus of Wyoming and Utah, previously described, are largely due to the action of wind-driven sand. "Blocks of sandstone or limestone which have fallen from an adjacent cliff are attacked, chiefly at their base, by the stratum of drifting sand, until by degrees they seem to stand on narrow pedestals. As these supports are reduced in diameter, the blocks eventually tumble over, and a new basal erosion leads to a renewal of the same stages of waste." [1]

Action of Heat and Cold.—The mere vicissitudes of heat and cold, without any assistance from freezing water, sometimes exercise important effects, by means of the alternate expansion and contraction which they cause. This is especially noticeable in countries where the daily range of temperature is very great, and is sometimes sufficient to

[1] Geikie, "Textbook of Geology," p. 320, and Gilbert in Wheeler's "Report of the U. S. G. Surv. W. of 100th Meridian," iii. p. 82.

crack and split off pieces of rock. Dr. Livingstone mentions that, in the interior of Africa, he found rocks which had their surfaces so rapidly cooled by radiation at night that the contraction was sufficient to split the stone, and to throw off sharp angular fragments, from a few ounces to one or two hundred pounds in weight. The following are his own words:[1]—

"Several of the mountain sides in this country (Gova) are remarkably steep, and the loose blocks on them sharp and angular, without a trace of weathering. For a time, we considered the angularity of the loose fragments as evidence that the continent was of comparatively recent formation; but we afterwards saw the operation actually going on, by which the boulders are split into these sharp fragments. The rocks are heated by the torrid sun during the day to such an extent that the thermometer placed on them rises to 137° in the sun. These heated surfaces, cooling from without in the evening air, contract more externally than within, and the unyielding interior forces off the outer parts to a distance of 1 or 2 feet. Let anyone in a rocky place observe the fragments that have thus been shot off, and he will find in the vicinity pieces from a few ounces to 100 or 200 lbs. weight, which exactly fit the new surface of the original block; and he may hear in the evenings among the hills, where sound travels readily, the ringing echo of the report, which the natives ascribe to the Mebesi, or evil spirits, and the more enlightened to these natural causes."

In warm climates, the continued heat of the summer sun sometimes produces enormous cracks in the earth. In the Sierra Nevada of Southern Spain, where there are districts composed of loose tertiary marls, great fissures have been formed several miles in length, two or three hundred feet deep, and several hundred yards in width. These ravines Professor Ansted describes as having originated in sun-cracks, though they may possibly have been deepened by the winter rains subsequently directed into them.

Great and rapid vicissitudes of temperature, by loosening the component particles of rocks, and causing the forma-

[1] Livingstone's "Zambesi," p. 492.

tion of cracks, thus facilitate the action of the more powerful agencies of rain and wind.

Action of Frost.—The destructive action exerted by freezing water is due to a peculiar property which it possesses, wherein it differs from most other fluids. Most other bodies contract in bulk as they cool down from a fluid state to the point of solidification; water follows this law of contraction till it reaches the temperature of $39\frac{1}{4}^{\circ}$ Fahrenheit (4° Cent.) in the downward scale, it then begins to expand, and continues to do so until it becomes solid at the temperature of 32° Fahr. or 0° Cent.

If, therefore, rain or other water soaks into the substance of rocks and fills up the interstices, cracks, and crevices which they contain, and this water then freezes, its conversion into ice is accompanied by an expansion which exercises an irresistible mechanical force and produces important geological results. Not only are the particles of the rock loosened and disintegrated, but the expansion of the freezing water in the larger cracks and fissures, by which all rocks are traversed, causes the fracture and displacement of large blocks, which are ultimately rent asunder and broken up into smaller pieces.

It is on the sides and summits of mountains, which are subject to great vicissitudes of temperature, that this agency acts with the greatest power and effect. The hardest rocks are broken up by it, and enormous masses are displaced and toppled down precipices, or are set rolling down slopes to suffer still further fracture, and produce still greater ruin in their fall. Its effects may be seen and its amount measured by the piles of angular fragments of all sizes, which are found at the foot of all crags and precipices, and which sometimes form talus- and débris-slopes many hundred feet in height.

Mr. J. F. Campbell thus describes the action of frost in Scotland:—"The silence of the still frosty night is some times broken by loud sharp reports followed by the hoarse rumble of stones falling from the mountain peaks. Rain-water sinks into every open chink, and when it freezes the crystal wedge shoves great rocks from their base. The tool-mark is an angular fracture whose shape depends on the nature of the rock which is broken. The finished work

is to be seen in high mountains, whose tops are riven peaks, and whose sides lie shivered where they fell."[1]

Captain Beechey in his "Voyage towards the North Pole" describes the amount of this action as very great in Spitzbergen. He found that the mountain sides were undergoing rapid disintegration from the absorption of wet during summer and its expansion by frost in winter. "Masses of rock were in consequence repeatedly detached from the hills, accompanied by a loud report, and falling from a great height were shattered to fragments at the base of the mountain, there to undergo a more active disintegration."

In describing the various erosive agencies now acting upon the slopes and summits of the Rocky Mountains, Mr. Clarence King thus describes the work done by frost and changes of temperature on the summit peaks:[2]—"The whole peak region is seen to be riven with innumerable cracks, which are due to unequal expansion and contraction in a region alternately chilled by radiation and warmed by the sun. Upon the steep slopes and sharp blade-like ridges, the results of such fissuring, together with the leverage of expanding ice, have the effect to dislodge large fragments of rock, and produce immense slopes of débris." He observes that this action takes place at all hours of the day, "but especially when a sudden chill (as during the hour after sunset) has the effect of congealing the percolating waters;" and he adds—"Upon the summits of the Rocky Mountains, the Uinta, and Wahsatch, and at very many points of the ranges near the Pacific coast, I have heard during the day thousands of blocks dislodge themselves and bound down the slopes. The resulting accumulations of débris form a very conspicuous feature throughout the Cordilleras. In many instances they must amount to fully 1,000 feet in thickness. In the Sierra Nevada, where all these phenomena are on a grander scale, I have seen débris-slopes measuring 4,000 feet from top to bottom."

The summits of the Alps present similar appearances, those which are not covered with perpetual snow termi-

[1] "Frost and Fire," vol. ii. p. 181.

[2] "Exploration of the 40th Parallel," vol. i. p. 471.

nating in jagged peaks and narrow points which are sometimes called *aiguilles* or needles. On these exposed peaks disintegration proceeds at a rapid rate, and showers of stones fall continually night and day, but especially in the afternoon when the sun's rays are hottest and the expanding force is consequently greatest.

The accompanying sketch, fig. 17, representing the forms

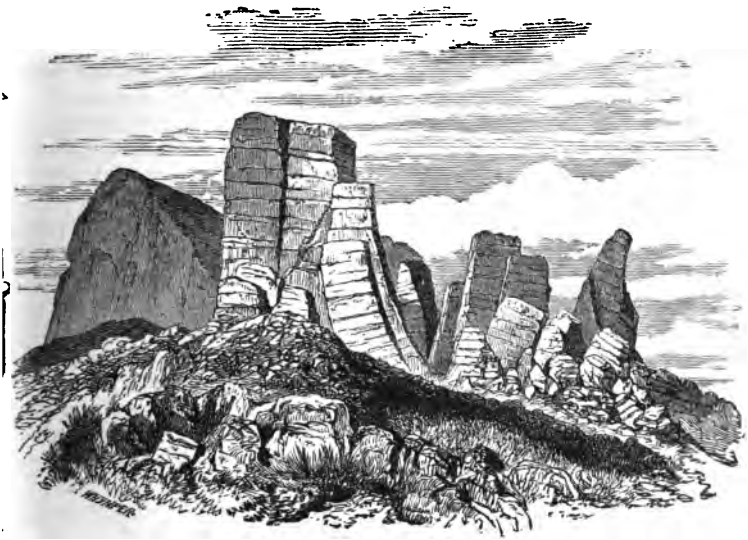

Fig. 17.

of some of these peaks, is taken, by permission, from Prof. Bonney's "Alpine Regions."

General Results of Atmospheric Detrition.—Of all the disintegrating agencies above mentioned, rain is the most important and universal; there are very few districts on the face of the earth which are absolutely rainless, and wherever it falls it operates both chemically and mechanically over large areas at once. There are, therefore, few rock-surfaces in the world which are not affected by this agency, assisted in most cases either by extreme heat or extreme cold, or by both combined.

The consequence of the erosive action of these atmospheric agencies is the production of a superficial covering of disintegrated rock or soil; but this soil is being continually removed from all sloping surfaces by the mechanical action of rain, and is thus constantly travelling to lower and lower levels, while fresh rock-surfaces above are being as constantly exposed to further disintegration by the weather. The general result of this continual action is that all land surfaces are being slowly, but surely, wasted away, and the soil, particle by particle, is being carried away into the rivers, and by them into the sea. It is clear, therefore, that were there no counteracting influences of upheaval, such as have been mentioned in Chapter IV., the continents of the primeval world would have been long ago destroyed, and a universal but shallow ocean would now envelope the surface of the globe.

This decay and wasting of the surface is, however, by no means uniform; it is most rapid in countries which have a large rainfall, and least appreciable in those which enjoy a dry and equable climate, like that of Egypt. Moreover, it is always greater in mountainous regions than on plains and gentle slopes. Again, as we have seen, some rocks yield much more rapidly than others, and this difference in the rate of waste produces inequalities in the surface, which are especially noticeable where two rocks of very different constitution are brought into conjunction with one another at the surface; one will always be worn down to a lower level than the other.

It should also be remarked that the rapidity with which different rocks yield to the weathering agencies has no relation to their hardness. Where other conditions are equal, soft clay resists their action better than the hardest limestone, because the latter yields so readily to the chemical action of carbonated waters which have no effect upon the former. We have seen, too, that even such hard rocks as granite and gneiss are often decomposed and disintegrated *in situ* to an astonishing depth.

CHAPTER VI.

UNDERGROUND CIRCULATION OF WATER.

A LARGE proportion of the rain-water which falls upon the earth sinks beneath the surface of the soil, and after percolating through the rocks below for a greater or less distance, is thrown out again in the form of springs. The depth to which it sinks depends on the nature of the rocks which it encounters in its downward passage. Some rocks are much more pervious than others; sand and sandstone are pervious by reason of their loose and porous nature; limestone and other hard rocks by reason of the numerous cracks and joints by which they are traversed; while all kinds of clay and shale are comparatively impervious to water, though their constant wetness shows that they are not absolutely impermeable.

Causes of Springs.—The position of springs is therefore always determined by the nature and relative position of the rock-beds, and is generally due to one of the following causes. The underground water is brought again to the surface—

1. By meeting with an impervious stratum.
2. By meeting with a fault or line of displacement.
3. By meeting with some open crack or fissure.
4. By the simple force of hydrostatic pressure.
5. By accumulation in an underground cavity.

1. If rain falls on a pervious rock it descends vertically, but if it reaches a more impervious stratum below, it flows laterally along the top of this bed and breaks out in springs along the line where this comes to the surface of the ground. The strength of the resulting springs will depend upon the relation between the slope of the ground and the slope of the rock-beds beneath.

Fig. 18 is an imaginary cut or section through a hill composed of sand or soft sandstone (*a*, *a*), underlaid by a stratum of clay (*c*, *c*), the surface of which slopes (or dips)

slightly towards the west. It is clear that the rain which falls on this hill will pass down through the sand and flowing outwards along the surface of the clay will issue in springs along a line on the western side of the hill, s^1, being a point on this line.

That there should also be a spring at s^2 on the eastern side is not at first sight so obvious, since the fall of the beds is towards, s^1, and water cannot run up hill: it must be remembered, however, that in passing downwards and outwards through the sandstone, the water will have to overcome a considerable amount of friction, and that this friction will tend to hold the water up under the hill. If, therefore, the rainfall be tolerably constant, the water will be accumulated in the lower portion of the sandstone more quickly than it

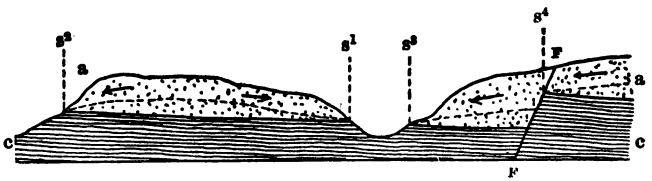

Fig. 18. Origin of Springs.
The line of saturation is indicated by the dotted line.

can escape by the springs, and consequently a certain thickness of the rock will be in a state of constant saturation. The thickness of the saturated portion will decrease towards the sides where the water finds egress, and its upper limit will form a curved line; this is called the *line of saturation*, and when this line rises above the level of the point s^2, the hydrostatic pressure will force the water outwards, and cause a spring at that point as well as at s^1. The former, however, will of course be a weaker spring, and will be the first to fail in a dry season, when the line of saturation under the hill is gradually depressed.

2. The instance above given is a very simple case, though it is one of frequent occurrence in nature. In other cases, however, strong springs do not occur where they might be expected on the above principle, the regularity of the underground waterflow being interfered with by the existence of

open cracks and fissures. It frequently happens that the rocks have been more or less vertically displaced along the plane of such cracks, so that the continuity of the several strata is interrupted. In fig. 18, FF. is a line of fault or displacement, on the western side of which the rocks are thrown up to a higher level, so that a face of clay is brought against the lower part of the sandstone on the eastern side. In this case, though there may be small springs at the point s^3, yet the main body of water percolating through the sandstone, will pass laterally along the line of fracture, and will be thrown out at some point, s^4, along its course where the surface of the ground descends below the level of the saturation line.

3. Springs sometimes issue from hill-sides without any obvious cause for the expulsion of the water. If, however, rain-water, after sinking for a short distance into the hill, meets with some horizontal crack or plane of division, it may find it easier to pass along it, than to penetrate further downwards. The hydrostatic pressure of the accumulating waters above and behind, will force the water along the crack, even if it should slope slightly upwards toward the surface.

4. Springs may also be caused by simple hydrostatic pressure overcoming the force of gravity under the following circumstances. In some districts the rocks are of such a nature that water may slowly descend through them for several thousand feet without meeting with any impervious stratum or great line of fracture. At such great depths, however, the rocks become denser and the cracks and joints much narrower and fewer, so that it may become very difficult for the water to work its way further downwards; it will then accumulate drop by drop and the pressure of the descending supply will become very great; the water will work its way through lateral cracks and joints, and if it meet with some large fissure or fault opening upwards, it may be easier for it to ascend than to sink further; in other words, the hydrostatic pressure may be sufficient to drive it up to the surface again, where it would issue in powerful and perennial springs. Waters which rise from great depths in this manner generally have a high temperature like those of Bath, and are known by the name

of "thermal springs;" but they must be distinguished from the thermal springs which occur in volcanic districts and are hot in consequence of the high temperature of the rocks near volcanoes.

5. *Intermittent Springs.*—If any cavities exist underground in which water can accumulate, it will do so until it reaches a height from which it can overflow, finding its way to the surface by the nearest outlet. It is not necessary that such cavities should be water-tight, and they may form part of an underground water-way, but if the channels of ingress are able to supply a greater quantity of water than the ordinary channels of egress can carry off, some other outlet at a higher level will act as a waste-pipe to carry off the superabundant supply and an intermittent spring will be formed.

The nailbournes and winterbournes of the south of England are caused by a gradual rise in the line of saturation under the chalk-hills till the water reaches a level at which there is free egress into some valley or depression; this, of course, only occurs after periods of great rainfall, and it is only then that these "bournes" begin to flow.

Action of Underground Water.—The waters which sink below the surface and find a passage through the rocks exercise both a chemical and mechanical action.

The power of carbonated water to dissolve certain substances has already been explained (p. 69), and it is evident that this chemical energy will enable the percolating waters to take up any soluble constituents of the rocks through which they pass. The consequences of this solvent power are twofold: not only will the water become charged with many mineral substances in solution, such as the carbonates of lime, iron, and magnesia; but the pores, spaces, and cracks within the rocks will be widened and enlarged by the removal of these materials. The results of this chemical action are most conspicuous among calcareous rocks, through which long underground caves and passages have been excavated by the flow of subterranean waters.

As a mechanical agent, underground water acts partly as a lubricator, and partly by removing small particles of the rock in suspension, either because they have previously been loosened by its chemical influence, or because the

rock is of a loose and incoherent nature like sand. The results of this action are most evident along cliffs and slopes, especially where conditions are favourable to the formation of springs. Cracks are widened and particles are removed till the cohesion of large masses is so weakened that they fall or founder down to lower levels. Such disruptions are called landslips.

Chemical Effects:—*Pipes and Swallow Holes.*—The dissolving action of rain-water is shown by the holes and hollows which occur in the surface of all limestone districts, any little depression where water can lodge is made deeper, the joints in the rock below are widened, and a funnel-shaped cavity or *swallow hole* is the ultimate result.

If the surface is covered by any kind of soil, with a growth of trees and plants which push their roots down to and into the rock, the rain-water is continually guided by these roots to certain points. The rock is consequently dissolved more rapidly below these points, and a hollow or pipe is gradually formed, into which the overlying soil sinks. Long chimney-like holes are sometimes produced in this way, filled with materials derived from the surface soil and descending for a long distance downward through the rock. Small pipes and pockets may be seen in many chalk-pits, varying in depth from a few feet to many yards, and generally filled with gravel, sand, or loam derived from the overlying soil. Excellent instances are visible in the chalk quarries by the side of the Great Northern Railway at Hitchin. Several huge funnel-shaped pipes, filled with gravel, are here seen descending vertically into the chalk, and passing down below the level of the railway.

These pits or pipes are still in process of formation. Dr. Darwin says:[1]—"During the last forty years I have seen or heard of five cases, in which a circular space, several feet in diameter, suddenly fell in, leaving on the field an open hole with perpendicular sides, some feet in depth. This occurred in one of my own fields whilst it was being rolled, and the hinder-quarters of the shaft-horse fell in; two or three cartloads of rubbish were required to fill up the hole. . . . The rain-water over this whole dis-

[1] "Vegetable Mould and Earth Worms," p. 137.

trict sinks perpendicularly into the ground, but the chalk is more porous in certain places than in others. Thus the drainage from the overlying clay is directed to certain points, where a greater amount of calcareous matter is dissolved than elsewhere." In districts where there is little or no soil, the *swallets* or pot-holes remain open, and are often wide and deep cavities into which the surface waters run and disappear. Such holes are common in the limestone districts of Yorkshire, and an account of them has been published by Mr. L. C. Miall, who mentions Thund Pot and Hellen Pot as among the largest.

There would appear to be two modes in which such swallow holes can originate. Some are due to direct solution from surface waters, and occur singly or in scattered groups; others occur in linear groups, and are due to unequal subsidence over a line of fissure. The latter are chiefly found where the limestone has a covering of shale, clay, or peat; the fissures below are then widened by aqueous solution, till the roof can no longer support itself at certain points, but falls in and pits the surface; the result is a succession of swallow holes, in which streams are often engulphed.

Mr. Whitaker remarks that in Berkshire there are always swallow holes at or near the junction of the chalk and tertiary beds, and that the small streams flowing off the latter often run into them; sometimes disappearing into a funnel-shaped hollow, sometimes flowing into a small pool, the level of which never alters, notwithstanding the continual flow of water.[1]

In other countries swallow holes occur on a still larger scale. Dr. Emil Holub describes a thick limestone formation as extending over hundreds of square miles in the Transvaal and Griqualand West (South Africa), and notices the frequent occurrence over this tract of funnel-shaped chasms, sometimes as much as 200 or 300 yards in circumference, and from 25 to 40 feet in depth. "At first sight," he says, "they have the appearance of being circular, but on investigation they nearly always prove triangular or quadrilateral. The interstices of broken rock with which

[1] See also O. Fisher, "On some Natural Pits on the Heaths of Dorsetshire," "Quart. Journ. Geol. Soc." vol. xv. p. 187.

their inner surface is lined are filled up by the surrounding earth, which thus forms a luxuriant bed for the roots of trees and shrubs, which tower up above, and become conspicuous upon the generally barren plain." From the bottom of these funnels fissures and underground passages radiate in different directions, and Dr. Holub describes his descent into one which bears the name of Wonderfontein. From others the water does not appear to escape so readily, and consequently the funnels form small lakes or pools of clear water.[1]

Subterranean Channels and Caverns.—The underground waters are often gathered into streams of considerable size, and surface rivers are sometimes engulphed in rifts or caverns, and flow for long distances in subterranean channels before they again emerge to the surface.

Such is the stream which traverses the great caverns of the Peak in Derbyshire.

In Staffordshire the river Manifold enters a cavern in the limestone hills near Ecton mine, and after flowing underground for a distance of three miles, reappears near Ilam.

In Yorkshire, the river Aire issues from Malham Tarn, a circular lake about a mile in diameter, on the summit of a lofty moor, and after flowing a short distance it descends into a subterranean channel, whence it issues again at the foot of Malham Cove, a perpendicular limestone rock 288 feet high.[2]

Sometimes, when the courses of such rivers are not far below the surface of the ground, a portion of the roof falls in, and leaves a deep trench, at the bottom of which the brawling waters of the stream may be distinguished among the masses of fallen rock. Good instances of this kind occur in the courses of the streams which flow beneath the great limestone plains of central Ireland, and have been thus described by Mr. Jukes:[3] "Sometimes the roof of one of the subterranean river-courses has fallen in for some distance, so as to form a narrow rocky valley, from a

[1] "Seven Years in South Africa," by Dr. Emil Holub, vol. i. p. 170.

[2] Conybeare and Phillips, "Geology of England," p. 397, note.

[3] "Manual of Geology," third edition, p. 458.

hundred yards to a mile or two in length. The river comes from under the limestone mass at one end, and runs below it at the other, the rock at either extremity of the fallen-in valley rising like a wall along the face of some strong joint. In the country, above and below one of these excavations, no one would have any suspicion of the course, or even of the existence of the subterranean river."

Instructive examples occur also in Greece. "It appears that in the more elevated districts of the Morea there are many deep land-locked valleys or basins, closed round on all sides by mountains of fissured and cavernous limestone. When the torrents descending from the surrounding heights are swollen by the rains, they rush into the enclosed basins; but instead of giving rise to lakes, they are received into gulfs or chasms, called by the Greeks *Katavothra*, which correspond to what are termed swallow holes in the North of England."[1] In summer it is possible to penetrate far into these chasms, and within is found a suite of chambers communicating with each other by narrow passages. The outlets are usually near the sea-shores of the Morea, but are sometimes situate beneath the sea.

To the solvent action of such streams then, aided doubtless by the influence of waters percolating through the roof, must be ascribed all the underground passages and caverns which occur in so many parts of the world, and which are sometimes of great size and length.

The caves of Franconia, in Germany, have for many centuries been celebrated for their beauty, and for the fossil remains which they contain. One of the most remarkable is the Cave of Gaylenreuth, the entrance to which is in the face of a perpendicular rock on the left bank of the Wiesent. This opening (*a* in fig. 19) leads into a series of chambers, which are from 15 to 20 feet high, and extend for a distance of several hundred feet; they terminate in a deep chasm (*b*), which is partially filled up with deposits of earth enclosing the bones of the various animals which formerly inhabited the cavern, bears, wolves, hyænas, &c. These cave-deposits will be described on a future page (Chapter IX.).

[1] M. Boblaye, in Lyell's "Principles of Geology," tenth edition, vol. ii. p. 516.

One of the largest caverns in the world is that at Adelsburg, near Trieste, consisting of long series of lofty grottoes and connecting passages through which the river Poik now flows.

The cavern of the Peak, in Derbyshire, is 2,250 feet in length, and consists of a succession of narrow passages and lofty chambers, some of the latter being 200 feet broad, and more than 100 feet high. Clapham Cave, which runs a long distance beneath Ingleborough, in West Yorkshire, is another remarkable instance.

The Mammoth Cave, in Kentucky, U.S., is well known. This has many branches extending in different directions,

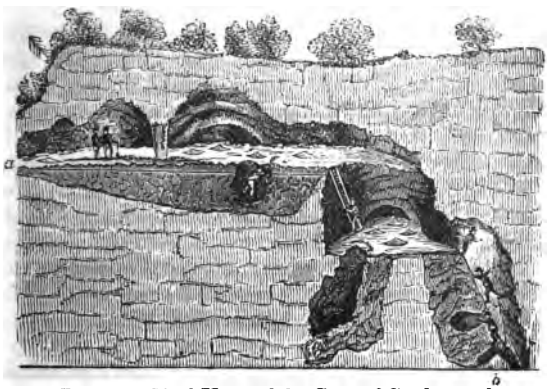

Fig. 19. Ideal View of the Cave of Gaylenreuth.

and one of them has been followed for a distance of ten miles without reaching its termination. Like other caverns, it is a system of large cavities connected by narrow tunnels; one of the chambers occupies an area of no less than ten acres, and has a height of 150 feet in some places.

It is not only in ancient limestones that such caverns occur; they abound in the limestone rocks of elevated coral islands, where the excavation of such cavities must have been comparatively rapid. The Rev. J. Williams states that in the island of Atiu, one of the Sandwich Islands, there are seven or eight of large extent. He

entered one, and wandered a mile along one of its branches, without finding an end to its "interminable wanderings." [1]

Mechanical Effects: Landslips.—Any slope of clay or shale has a tendency to slip after heavy rain, as may be seen in many of our railway cuttings. In dry weather the contraction of the clay leads to the formation of internal cracks, and when rain falls the water flows down these, removes particles from their sides, and so lubricates the contiguous surfaces that portions slip and founder down by their own weight. The foundering of clay slopes can be well studied in the Isle of Sheppey, where large portions of ground slip seaward every winter. The manner in which these slips are produced has been thus described:[2]—"In the hot weather the surface of the ground is cracked from the shrinking of the clay, and the cracks are seen as gaping fissures about six inches across and many yards in length and depth. When the rain falls, it finds its way into these cracks and softens the clay at the bottom. If the crack is near the cliff, the half detached mass being now heavier, owing to the addition of the water, while the cohesion of the attached portion is lessened, slips down to the shore below, sometimes almost unbroken, sometimes breaking off by parallel cracks into a series of terraces, or even in part creeping down among the fallen stiffer masses as a glacier-like mud-flow. The sea washes this débris away from the base of the cliff, and the process is repeated."

In harder rocks the open cracks and joints afford access to the rain-water, and frost often assists in the process.

Of such slips, on a large scale, the falls of the Rossberg, in Switzerland, are examples. In 1806, and again recently, in 1881, large slices broke away from the side of the mountain, and fell into the valley of Goldau, burying villages, and causing great destruction and loss of life. Similar masses are sometimes shaken down from the sides of mountains during earthquakes, blocking up valleys, and turning the streams which flow down them into temporary lakes. A head of water is thus accumulated which, when

[1] See Dana's "Coral Reefs," p. 361.

[2] Professor Hughes, in Whitaker's "Geology of the London Basin," Mem. Geol. Survey, p. 387.

the dam gives way, affords a far more destructive water-power than that of a mere stream.

Professor Heim has recently called attention to the importance of these massive landslips (*Bergstürze*) in mountainous regions; and the Rev. A. Irving has dwelt upon the part which they play in the formation of many lakes.[1]

Three principal types of such landslips may be recognized in Switzerland:—

1. Cases in which thick accumulations of *débris* upon mountain sides become saturated with water after heavy rains. The water, by increasing the weight of the mass, and diminishing the friction, causes the whole to slide down the slope. "One of the most remarkable instances of this class is the movement which is now going on at the village of Fetan, in Unter Engadin. Houses are tilted, or parted asunder; and the solid rock on which the tower of the church stands is found to be but a great [detached] mass of granite, which is slowly moving with the looser materials in which it lies embedded."[2]

2. Cases in which the strata forming a mountain slope towards a valley on one side of it, so that portions become loosened by the action of rain and frost, and slip bodily down into the valley below. The falls from the Rossberg above mentioned belong to this type.

3. Cases in which huge masses of rock are detached from the higher slopes, and form avalanches of rock and earth, which descend into the valleys. Such falls frequently destroy whole villages, and sometimes lead to the formation of lakes, either permanent or temporary; and the bursting of the latter causes destructive floods below the site of the barrier. Thus, in 1512, a mass fell from Monte Crenone, above Biasca, destroying 400 houses, and killing 600 people. "The river Blegno was dammed up by it, and formed a lake, which remained for three years, when the barrier was broken through, and the whole valley, down to Lake Maggiore, devastated by floods." In 1618, the village of Plurs, in Bergell, was totally overwhelmed, and still remains completely buried. By a similar fall from the Diablerets, the

[1] "Geol. Mag.," Dec. 2, vol. x. p. 160.
[2] Heim, quoted by Irving, op. cit. p. 161.

present lake of Derborence was formed by the damming up of the river Licerne.

The recent landslip in the valley of the Rhone (January, 1883) is another instance. Between Bellegarde and Evian, the Rhone runs through a narrow rocky gorge, bounded on one side by a lofty spur of the Jura, and on the other by the precipice of Mont Vuache, along a ledge of which the railway is here carried. From this mountain, an enormous mass of earth and rock fell, destroying a short tunnel on the railway, and stretching across to the other side of the valley, so as completely to block the course of the Rhone. The waters immediately began to gather behind the barrier; and had it been strong enough to dam them back for a long time, the consequences would have been tremendous, but fortunately the river soon forced a passage through the mass of débris.

"No Alpine valley," says Professor Heim, "is without such heaps of débris and traditions having reference to them. A still older series belongs to a time extending far back beyond the range even of tradition." He particularly describes an enormous fall near Flims, which is 2,000 feet high, and appears to have taken place at a time anterior to the glacial epoch.

In the British Isles, landslips are most frequent where the superposition of pervious upon impervious rocks cause the issue of springs along the foot of a slope or cliff. In such cases, the water is perpetually sapping the foundations of the upper beds, and lubricating the surface of the impervious stratum below, till large masses founder down at once, and form a series of confused mounds and terraces.

The well-known Undercliff of the Isle of Wight is an example of this, being in reality a succession of landslips, caused by the slipping of masses of chalk and greensand over the surface of the dark blue clay which underlies them. This clay is locally termed "the blue slipper," but is known to geologists under the name of *gault*. The fallen masses form a series of irregular terraces between the real cliff and the shore, and extend for a distance of six miles along the coast. This undercliff and its formation is indicated in Fig. 20, which is a diagrammatic section from

north to south (from Mantell's "Excursions in the Isle of Wight").

The history of a single landslip, such as that of the great Axmouth slip, which occurred in 1839, will be instructive. The arrangement of the beds on this coast is similar to that in the Isle of Wight—beds of chalk and greensand resting on a retentive stratum of clay, the surface of which has a slight slope seaward. The following account is abridged from Sir Charles Lyell's description:[1]—In 1839, an excessively wet season had saturated all the rocks with moisture, so as to increase the weight of the incumbent mass from which the support had already been withdrawn by the action of springs. Winter came on, and frost exer-

Fig. 20. The Undercliff, Isle of Wight.

cised its usual expansive effects on the water in all the vertical cracks and fissures, and naturally tended to force the masses outwards and seawards, while their slippery basis of watery sand decreased the friction, and rendered their descent over the surface of the clay a comparatively easy process. These causes gave rise to a convulsion, which began, on the morning of the 24th of December, with a crashing noise. On the evening of the same day, fissures were seen opening in the ground, and the walls of tenements rending and sinking, until a deep chasm or ravine was formed, extending nearly three-quarters of a mile in length, with a depth of from 100 to 150 feet, and a breadth exceeding 240 feet. The tract intervening between this fissure and the sea, including the ancient undercliff, was carried bodily forward, and the pressure of this enormous

[1] "Principles of Geology," tenth edition, vol. i. p. 536.

mass forced up the shore in front of it, producing a long, upraised ridge, covered with large blocks of rock, which, at the time of the occurrence, were invested with seaweed and corallines, and scattered over with shells and star-fish.

"Far larger instances of ancient landslips, of which no record is known, and which took place, perhaps, before historic times, or even before the country was inhabited by man, may be observed in some parts of the south-west coast of Ireland. On the coast west of Bearhaven, in county Cork, and west of Brandon Head, in county Kerry, as also in Derrymore Glen, between the mountains called Baurtregaum and Cahirconrea, there are great cliffs, where the rocks are thrown into positions which appeared puzzling and abnormal, until it was ascertained that they formed parts of gigantic landslips. Masses of land, with cliffs 800 feet high, were then seen to be nothing but a confused heap of broken ruins, their cracks and dislocations being superficial only, and not extending below the level of the sea."[1]

[1] Jukes' "Manual of Geology," second edition, p. 102.

CHAPTER VII.

FLUVIATILE AGENCIES.

§ 1.—*Action of Running Water.*

EROSIVE Power of Running Water.—That running streams have the power of deepening and widening the channels in which they flow, is now a well established and most important fact. If a newly-made bank of earth is observed after a shower of rain, it will be noticed that the slope is furrowed from top to bottom by little runnels and channels, which have been excavated by the rills and streamlets into which the rain-drops collected as they coursed down the slope. This is a miniature representation of what takes place on the sides of a valley or the slopes of a watershed.

Sir Charles Lyell describes a ravine near Milledgeville in Georgia, U.S., entirely formed by the torrential action of rain-streams consequent upon the cutting down of the forests, which had previously prevented the rain from collecting into large streams. When the land was cleared cracks 3 feet deep were caused by the heat of the sun; and during the rains the rush of water deepened the principal crack at its lower extremity, whence the excavating power worked backwards, till, in the course of twenty years, a chasm was produced no less than 55 feet deep, 300 yards long, and varying in width from 20 to 180 feet.[1]

It is not the mere force and impact of the descending water which gives a stream this excavating power; it is the quantity of detritus, large and small, which it carries along and hurls against the sides and bottom of its channel. The fine sand and mud which the rain washes off the surface of the land, are the initial instruments of erosion; these are held in suspension by the water, and

[1] "Principles of Geology," tenth edition, vol. i. p. 344.

exercise a constant attrition upon all the rock surfaces with which they come in contact. In rapid streams and mountain torrents, stones and pebbles are rolled along the bottom, and these, as well as the sand and mud which are held in mechanical suspension, all help in the process of erosion. This process is therefore one of mechanical wear; the tools are pebbles, sand, and mud, the effective force which moves them is that of running water.

The blocks accumulated in such torrents are usually fragments of rock which have fallen from the neighbouring crags into the water-course. These blocks, arresting the force of the stream, are worn and fretted by the particles of sand and mud with which the water is charged, till they become smooth and rounded by the constant attrition. Some greater flood than usual then sets them in motion, they are knocked and ground against one another till they are broken up and converted into a number of smaller stones or pebbles. These are rolled onward into the brook, where they undergo a continuation of the same mechanical operation, being perpetually ground into smaller and smaller fragments, till they eventually become grains of sand and particles of mud. In this shape they are delivered into the river, and after many detentions by the way, are ultimately swept into the sea.

Vertical and Lateral Erosion.—The erosive action of mountain torrents can hardly fail to be perceived by anyone who visits them and observes the beds of their narrow channels. These exhibit smooth grooves and cuts even in the hardest rocks, which are obviously due to attrition; while vertical pits, called *pot-holes*, several feet in depth, are often formed in such rock by the whirling action of water keeping a few pebbles or a little coarse sand in perpetual circular motion. Cascades and waterfalls dig deep holes and black pools below the ledges over which they fall; these ledges, indeed, are often undermined by the dashing water, and are broken off, block by block, so that the cataract recedes farther and farther back; while a deep ravine is left in front, extending from the present falls to the point where they originally commenced. Niagara is an excellent instance of such erosion, the gorge below the cataract being seven miles in length from the

original site of the falls above Queenstown to their present position; and the present rate of their recession is estimated by Sir Charles Lyell at about 1 foot per annum.[1]

Recession of Spring Heads.—Springs are in some places an important factor in the formation of tributary valleys. So many tributary streams take their origin from springs, that it is clear the courses of such streams have been partly determined by the position of these outlets, and that their valleys may reasonably be regarded as the combined work of the springs and the rain.

Waters issuing from a hill-side, and acting both chemically and mechanically, naturally tend to remove material from the mouth of the spring, and so cause the position of the outlet to recede. This recession would be very slow, and is evidently so, in cases where the action of the spring has not been assisted by the action of rain. In most cases, however, more or less of the rain running off the surrounding surface is directed into the recess or depression caused by the spring; and then the process of recession is a much more rapid one. The rain sweeps down the soil from the sides of the hollow, and the waters of the spring keep the channel open, and transport the material to lower levels. The rapidity of this process will depend much on the nature of the rocks acted upon.

Lateral Erosion.—As soon as a stream reaches a part of its valley where the slope is less than 10 feet per mile, it begins to take a serpentine course, winding about from side to side of the valley bottom, and as soon as it begins to curve its erosive power is exercised laterally as well as vertically, and it begins to widen its valley.

The extent to which it can do this depends upon the slope of its channel and the volume of its waters, because the width and extent of the curves depend upon these conditions; thus it has been ascertained that[2]—(1) the radius of the curve is proportionate to the slope; (2) the extent or chord of the curve is proportionate to the volume. The first law means that streams with a quick fall tend to run in straight lines, as far as other conditions allow. A fall of 10 feet per mile is sufficient for this, but with a less

[1] Lyell's "Principles of Geology," vol. i. p. 359.

[2] See J. Fergusson in "Quart. Journ. Geol. Soc." vol. xix. p. 322.

fall the stream begins to curve, and if the fall be only 3 inches per mile, the curves are semicircles with a chord of about 4 times the width of stream. The second law means that large rivers make large curves, and small streams make small curves. Therefore a small stream with a tolerably quick current will run in a deep but narrow valley, while a large stream with a slow current will wind about in a valley, the width of which is much greater than its depth.

It must not be supposed, however, that the depth and width of a valley depend only on the volume and velocity of the stream; as long as the rocks through which it makes its way are of the same kind and degree of hardness, its erosive effect will be chiefly regulated by these conditions. But where, as usually happens, the valley traverses a series of different strata, its width and depth will vary according to the hardness and ability of each stratum to resist the erosive action of the stream, and the detritive power of rain.

Erosion Assisted by Rain.—In a humid climate like that of England and of northern Europe generally, and in districts where the rocks are comparatively soft, the valleys are broad and open, with gently sloping sides, and the hills have rounded outlines forming binomial curves.

These features are due to the disintegrating and detritive effects of rain on the valley-sides; the action of rain and frost, already described, causes the banks to crumble and moulder down, and every heavy shower of rain washes some of the soil so produced into the stream below, by which it is carried away to be deposited elsewhere.

In such districts, therefore, rain has as much to do with the formation of valleys as the rivers have,[1] and the valleys which are formed by the combined influence of these two agencies are always widely V-shaped, the sides sloping at a less angle in proportion as the rocks are soft and the rainfall great.

On the contrary, where the rocks are hard, the erosive action of the stream tends to excavate narrow steep-sided valleys or U-shaped gorges, the sides of which approach

[1] See "Rain and Rivers," by Col. G. Greenwood, 1857.

the vertical in proportion as the rock is hard and the local rainfall is small.

In places where a softer kind of rock rests upon a harder one, the valley will present a combination of the two forms as represented in fig. 21.

When the banks are soft and easily eroded, and the velocity of the stream is small, the conditions are most favourable for lateral erosion, and a wide, flat-bottomed valley, filled with alluvial detritus, is the result. This is well exemplified by the lower part of the valley of the Mississippi, where the stream has lost all power of vertical erosion, and pursues its meandering course through an alluvial plain of its own formation, which varies from 50 to 80 miles in width.

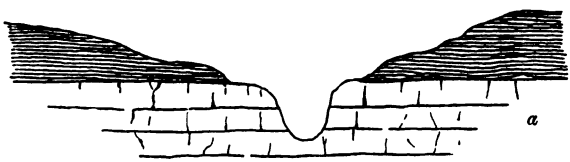

Fig. 21. Erosion of Valleys.

a = hard rock. *b* = soft shale.

Rapidity of Erosion.—From what has already been stated, it will be seen that the erosive power of any stream—*i.e.* the quantity of material which it can remove from its valley—depends upon four circumstances—

1. The volume of water, depending upon the annual rainfall, frequency of floods, and the porosity of the soil;
2. The velocity of stream, depending on the volume of water, and the slope of the watercourse;
3. The character of the rocks through which it flows;
4. The load or quantity of detritus which it carries.

Mr. A. Tylor has calculated that—

1. The velocity increases as the cube root of the volume of water, the slope remaining the same;
2. The erosive force increases as the fourth power of the velocity.

Hence, supposing a sudden rainfall to take place in the

catchment area of a river, increasing the volume of the stream to 27 times its ordinary amount, the river would flow with 3 times the velocity, and with 81 times its former erosive force. This explains the astonishing effects of rivers in times of flood. Large boulders are then moved, stones and pebbles are driven against the sides and bottom of the channel, and the whole work of attrition and excavation is carried on with greatly intensified force. A few instances will enable the reader to realize this more fully.

1. Professor Green mentions some results of a flood which was caused by the bursting of a reservoir near Sheffield, in 1864. He says: "At sharp bends in the valley, where the water had impinged on projecting spurs of the bank, or where it had been driven into a recess, it had excavated in the solid sandstone rock large hollows, which anyone, who was not aware of the circumstances of the case, would have supposed to be quarries. Many acres of meadow-land were deeply buried beneath heaps of débris, consisting mainly of large angular blocks of rock, which the torrent had torn off from the banks as it rushed along."[1]

2. Sir Charles Lyell has described the destruction worked at Tivoli by the waters of the Tiber, after heavy rains, in 1826. The stream burst its usual bounds, and, impinging on its right bank, had, in the course of a few hours, undermined a high cliff, and widened its channel by about 40 feet. The church of St. Lucia, and about thirty-six houses of the town of Tivoli, were carried away, presenting, as they sank into the flood, a terrific scene of destruction to the spectators on the opposite bank.[2]

3. Floods in Scotland, 1829.—Many illustrations of the power of rivers to move stones, and deepen or widen their valleys, were afforded by the floods which followed the storm of the 3rd and 4th of August, 1829. The effects were particularly apparent in Aberdeenshire. Bridges and roads were swept away, and great accumulations of stones and blocks of rock were left on the surface of fields, many feet above the ordinary level of the rivers. "Some new

[1] See Prestwich, in "Quart. Journ. Geol. Soc." viii. p. 224.
[2] "Principles of Geology," tenth edition, vol. i. p. 355.

ravines were formed on the sides of mountains where no streams had previously flowed; and ancient river-channels, which had never been filled from time immemorial, gave passage to a copious flood."

Sir Charles Lyell remarks: "It is evident, therefore, that when we are speculating on the excavating force which a river may have exerted in any particular valley, the most important question is, not the volume of the existing stream, nor even the nature of the rocks, but the probability of a succession of floods at some period since the time when the valley may have been first elevated above the sea." [1]

In temperate regions, these are exceptional occurrences; but, in tropical countries, floods are of constant occurrence during the rainy season; consequently, the erosive power of the streams is enormously increased, and all the results of detrition are on a much larger scale. As this is a fact which European geologists do not always realize, we adduce the testimony of one whose experience well qualified him to express an opinion on the subject:[2]—"In the British Islands, the average rainfall is about 24 inches, distributed over the greater portion of the year. In India it averages about 50 inches, by far the greater portion of which falls in three months. The showers are far heavier, and far more effective in sweeping soil, sand, and pebbles from the surface of the country into the streams; and floods in the latter are of annual occurrence, instead of only happening at rare intervals. The effect of a river in full flood, in sweeping detritus down into the sea, compared with the usual denudating action, is as the comparison of the effect produced by the breakers of the ocean in a storm to those of an inland sea on an ordinarily fair day.

"In flood, a river is liquid mud, rather than water. But, in addition to the great floods, minor floods in tropical streams are matters frequently of daily occurrence during the rainy season. After seeing, both in India and Abyssinia, what the effects of these agents are in tropical countries, I do not feel surprised that their powers should be recognized with difficulty in regions where their effects are comparatively so dwarfed as in the British Isles."

[1] "Principles of Geology," tenth edition, vol. i. p. 354.

[2] Blanford, "Geology and Zoology of Abyssinia," p. 157, note.

Dr. Livingstone also bears testimony to the amount of material transported by certain African rivers, which at some seasons actually have more sand in them than water. He says: "We came to the Zingesi, a sand rivulet in flood. It was 60 or 70 yards wide, and waist deep. In trying to ford this, I felt thousands of particles of coarse sand striking my legs. The shower of particles and gravel which struck against my legs gave me the idea that the amount of matter removed by every freshet must be very great. In most rivers, where much wearing is going on, a person diving to the bottom may hear literally thousands of stones knocking against each other. This attrition being carried on for hundreds of miles in different rivers, must have an effect greater than if all the pestles and mortars and mills of the world were grinding and wearing away the rocks."

Instances of River Erosion.—Having in the preceding pages indicated the manner in which streams excavate and widen their channels, and the causes which assist rivers in forming the valleys they occupy, we shall now describe several cases in which it is clear that ravines and valleys have been formed by rivers. The ravine at Milledgeville, described by Lyell, and mentioned on p. 97, is an instance of the excavating power of a stream formed by the concentration of rills of rain-water. The observations of Professor Jukes, in Java, furnish us with an equally convincing example.

1. *Gullies on Volcanic Cones in Java.*—Mr. Jukes says:[1] "One thing which struck me particularly in this central group of cones (in the crater of the Bromo) was, that the one in action was perfectly smooth and regular outside, like a loaf of sugar, while those that had shortly ceased to eject materials showed the irresistible progress of denudation in the commencement of rain-gullies radiating down their slopes. Those that were still older, as proved by young trees having commenced to grow on their flanks, had these gullies much deeper and broader, so that they began to show narrow ridges, separated by small ravines radiating from the summit, like the ribs of a half-opened umbrella,

[1] "Manual of Geology," third edition, p. 353.

as described by Junghun, when speaking of the outer slopes of the greater mountains."

In the same way, the outer slopes of the volcanoes in the South Pacific, described by Dana, are worn down to the condition of narrow ridges, with nearly vertical walls, separated by flat-bottomed valleys, which gradually contract towards the interior; and at the head of each valley may be seen a little rill of water leaping from crag to crag, still carrying on the work of erosion to which, at first sight, it seems so utterly inadequate.

2. *Gorge of the Simeto.*—Near the town of Aderno, where the river Simeto passes the western base of Etna, a current of lava has descended into the valley, and, in so doing, must have completely blocked up the course of the river. This took place, according to Gemmellaro, in the year 1603. Through this lava, which solidified into a hard, blue compact rock, resembling ordinary basalt, the Simeto has excavated a ravine from 40 to 50 feet deep, and from 50 to several hundred feet wide. Sir Charles Lyell thus describes the scene in 1828: "On entering the narrow ravine, we are entirely shut out from all view of the surrounding country; and a geologist, who is accustomed to associate the characteristic features of the landscape with the relative age of certain rocks, can scarcely dissuade himself from the belief that he is contemplating a scene in some rocky gorge of very ancient date. But the moment we reascend the cliff, the spell is broken . . . for we stand on the black and rugged surface of a vast current of lava, which seems unbroken, and which we can trace nearly up to the distant summit of that majestic cone which Pindar called the 'pillar of heaven.'" [1]

This ravine, therefore, has been eroded by the stream in the course of about two centuries; but, as Lyell observes, it has not yet cut down to the ancient bed of which it was dispossessed, and the probable position of which he indicates in a diagram.

3. *Valleys of Auvergne.*—What has happened once in the case of the Simeto has happened several times in many of the valleys of Central France. These valleys have been

[1] "Principles of Geology," tenth edition, vol. i. p. 358.

excavated to a great depth through strata of fresh-water origin, and have been flooded from time to time by streams of liquid lava from the neighbouring heights. Each successive lava-flow must necessarily have occupied the lowest levels to which it had access; but they now form terraces or platforms at various heights, from 1,500 feet downwards to the level of the present watercourses. These valleys were originally described by Mr. Poulett Scrope, who says:[1] "Take, for instance, the two basaltic platforms of Gergovia and La Serre, and the bed of basalt which occupies the bottom of the intervening valley of Chanonat. Here are three long sheets of lava, each of which, by its gradual inclination in the same direction, and by the remains of the volcanic vent from which it was erupted, is proved to have flowed down the valley." The platform of La Serre is everywhere from 300 to 500 feet below that of Gergovia

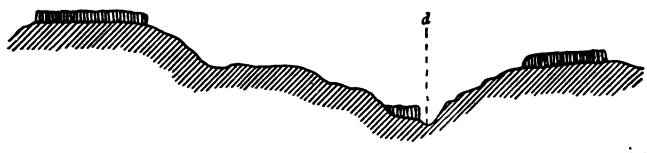

Fig. 22. Section across Valley of Chanonat, Auvergne.

and the valley must have been deepened by that depth during the interval between the two outflows. Again, by the same reasoning, the valley of Chanonat must have been entirely excavated between the epoch of the La Serre lava and the production of the more recent bed of basalt, 500 feet below. Finally, the Chanonat rivulet has worn a new channel, from 20 to 50 feet below the level of the pebble bed on which the most recent of the three lava currents reposes (see fig. 22).

From this and numerous other instances, he justly concludes that "the erosive force of the streams which now border or intersect these lava currents, together with the action of rain, frost, and other atmospheric forces, have alone hollowed out the extensive systems of valleys" which

[1] "The Volcanoes of Auvergne," 1825, and "Geol. Mag." vol. iii. p. 195.

are found in the province of Auvergne. Floods doubtless occurred from time to time, and materially assisted in the erosion; but it is very clear that these valleys do not owe their origin to any one unusual or cataclysmal flood, or to any sudden disruption of the rocks (see fig. 23).

Dr. A. Geikie has so excellently described the impression which the valleys of Auvergne make upon the mind of a geologist, that I venture to quote several passages in full:—

"No one, whose observations have been confined to a country which has been above the sea only since the glacial period, or the contours of which have been smoothed over by the ice-sheets of that time, can readily form an adequate idea of the denuding effect of water flowing over the surface of the land. . . . The first impression received from a landscape, like that round Le Puy, is rather one of utter bewilderment. The upsetting of all one's previous estimates of the power of rain and rivers is sudden and complete. It is not without an effort, and after having analyzed the scene, feature by feature, that the geologist can take it all in. But when he has done so, his views of the effects of subaerial disintegration become permanently altered, and he quits the district with a rooted conviction that there is almost no amount of waste and erosion of the solid framework of the land, which may not be brought about in time by the combined influence of springs, frost, rain, and rivers." [1]

4. *Valleys of the Eifel.*—The country of the Lower Eifel, where it is traversed by the rivers Rhine and Moselle, affords another excellent instance of the excavation of valleys by river erosion. The country is composed of beds of hard rock, bent and inclined in various directions, and the general surface forms a gently undulating table-land, about 1,000 or 1,200 feet above the level of the sea. Through this country the rivers flow at the bottom of deep and winding valleys, forming the magnificent curving slopes which are the chief feature in the scenery of the district. This is particularly striking in the case of the Moselle, which works its way in so tortuous a course that some of its bends form loops, and curve back, so as to

[1] "Geological Sketches," by A. Geikie, 1882, pp. 93, 121.

leave but a narrow ridge between the two reaches of the river. This singularly winding valley is both narrow and deep, being closely environed by steep, precipitous banks, 800 to 1,000 feet in height; and between their opposing bases, there is frequently no more room than is just sufficient for the river itself.

The country on either side is furrowed by numerous narrow ravines, with steep and often precipitous sides, which cut down, as they near the Moselle, to depths of 600

Fig. 23. The Valley of Montpesat in Auvergne.

or 800 feet below the surface of the plain, and curve from side to side in equally sinuous courses.

The only explanation which can be given of such a wonderful system of valleys is that the streams originally ran over the surface of the plain, and have constantly maintained the winding courses of their early channels, gradually engraving them deeper and deeper into the land, as the work of erosion and excavation proceeded. The action of rain has been co-extensive with that of the streams, wearing down the valley sides, and widening them into the shape they now possess.

5. The most wonderful instances, however, of the erosive

power of rivers are to be found in the deep and trench-like valleys of the Western States of North America.

The great ravine (or cañon) of the Colorado river is about 300 miles long, and consists of a valley about ten miles wide with precipitous sides from 4,000 to 5,000 feet in depth, the bottom of this being trenched by an inner gorge, 1,000 feet deeper still, with sides which rise like great walls from the river at the bottom to the plateau above. The country on both sides of this enormous ravine is channelled by innumerable narrow, deep, and winding cañons, all similar in their general characters, and each one occupied by a tributary of the main river.

These extraordinary ravines have been cut down through horizontal beds of sandstone, shale, and limestone, and into the granite which underlies them, the limestones being especially hard and massive, with an aggregate thickness of from 2,200 to 2,500 feet. The shales and sandstones lie above these limestones, and it is these beds which have been cut back so as to leave the broad shelf or plain on either side between the edges of the central ravine and the lines of cliff which bound the upper part of the valley. The outline of the whole valley is then similar to that in fig. 21, only that the edges of the upper portion are not sloping, but nearly vertical.[1]

The reason why these great ravines are such excellent instances of river erosion is because they were made almost entirely by the rivers alone with little assistance from any other detritive agencies. The district drained by the Colorado and its tributaries is an elevated basin-shaped plateau: and there is little doubt that, when the course of the river was first determined, the country stood at a much lower level, and the tributary streams ran in channels of no great depth. When the land began to rise these channels were gradually cut deeper and deeper, until their present depth was attained, this depth being an approximate measure of the amount of elevation which took place. The

[1] For descriptions and illustrations of these cañons, see "Exploration of the Colorado River," by Ives and Newberry, 1861, and the later "Memoirs" by J. W. Powell, 1875, and C. E. Dutton, 1882. Also Geikie's "Text Book of Geology," p. 923, and the Frontispiece in Jukes' "School Manual of Geology."

present height of the watershed above the sea is from 8,000 to 12,000 feet, and the erosion has continued uninterruptedly for an immense length of time, for the country has remained in the condition of dry land throughout a long succession of geological periods. Two circumstances have combined to maintain the verticality of the cañon walls during the process of erosion: the first is a decrease in the rainfall of the district, for at the present time it is practically rainless, and we have seen that gorges are steep and narrow in proportion as the rocks are hard and the rainfall small; secondly, the limestone beds through which they are cut are quite horizontal and undisturbed, the only cracks being vertical joints down which water could percolate and chemically disintegrate the rock.

The Base Level of Erosion.—We may therefore conclude that if a river is left to its own unassisted action in a rainless district, it will cut a deep trench, with walls

Fig. 24. Profile of River Slope reduced to a Base Level of Erosion.

steep in proportion to the hardness and horizontality of the rocks, and that it will deepen this trench as long as it has any appreciable slope.

Let us assume a tract of country with a central watershed of a given elevation above the sea, and a river flowing down one of its slopes: this river will continue to deepen its channel until the inclination of its bed is so lowered throughout its course that vertical erosion ceases to be possible, and the power of the flood waters is diverted to the process of lateral erosion.

When a river ceases to have any further capacity of vertical excavation, it may be said to have reached its *base level of erosion*,[1] and this line, as Mr. A. Tylor has shown, tends to approach a parabolic curve, the inclination of which increases upwards towards the source of the river; the greatest declivity being near the watershed (see fig. 24).

[1] This term was first proposed by Powell, "Exploration of the Colorado River," 1875, p. 203.

When a river has once attained this base line of erosion, its subsequent action will depend upon the general movements of elevation or depression which may take place in that region. As long as the land remains stationary the action of the river will be confined to that of widening the upper part of its valley, and depositing material in the lower part. If the land be depressed, the original bed of the valley will be sunk below the sea-level to a greater or less distance from the original mouth, and the process of deposition will begin at a less distance from the source of the river; this is the state of many rivers on the east coast of England (see p. 60).

If, on the contrary, a movement of upheaval set in, the river will recover its power of vertical erosion; the extent to which the valley will then be deepened will correspond to the amount of the elevation. If the rainfall on the watershed be increased by the upheaval of the country, the curve

Fig. 25.

of the base-line of erosion may be slightly altered, but will still gradually decrease from the source of the river to its termination in the sea.

The diagram (fig. 25), has been drawn to illustrate the influence which the elevation of a country must have upon the erosive power of the streams and rivers. Let *a*, *b*, represent the slope of a watercourse flowing from *a* to the coast at *b* when the sea-level coincided with the line s^1. Now suppose the country to be elevated until the sea-level came to correspond with the line s^2, the amount of elevation being represented by the space between s^1 and s^2, which may be 20 or 200 feet. The stream would immediately begin to deepen its channel at *b*, so as to bring its outfall down to the level of the new base-line s^2; this erosion would continue along the whole length of the valley until the stream had completely accommodated itself to the altered conditions, and had deepened its channel by an amount proportional to the increase of

slope. This amount is indicated in fig. 25 by the shaded portion, so that the bottom of the watercourse will eventually coincide with the curved line $a\ s^2$.

It becomes evident, therefore, that the influence which movements of subsidence or upheaval exercise upon the power of rivers to erode their channels is most important, and the author believes that it is mainly because the advocates of river-erosion have neglected to insist upon this point that many persons have been unable to see the cogency of their arguments, or to believe that rivers have had any share in the excavation of their valleys. It is said by these sceptics that the rivers are not now deepening the valleys in which they run, and, therefore, that the valleys cannot have been made by the rivers; some have answered this by supposing that the volume of water in the rivers was much greater formerly than it is now, but the real answer is that these streams have reached their base-lines of erosion, and consequently that observations on their present action will not enable us to realize how they have excavated the valleys in which they flow. This seems to be the case with many of the large European rivers, especially the Rhine and Moselle, whose valleys have just been described. It is necessary to remember that there must come a time in the history of every river when its power for vertical erosion must cease, and when the stream becomes merely a vehicle for transporting the material which is washed into it by the rain. The action of rain, however, will never cease as long as any rain falls, and consequently the widening of valleys must continue as long as there are any slopes for the rain to act upon.

Let us suppose this process to be carried out to its full extent in such a country as that through which the tributaries of the Moselle flow. The valleys will gradually be widened at the expense of the intervening ridges, which will come to assume the character of hill ranges; and finally, instead of an upper plain with deeply excavated valleys, we should have a lower plain with chains of hills more or less isolated from one another.

The manner in which a country is thus sculptured out into a series of hills and valleys will be treated at greater length in a future chapter (Part III.).

§ 2.—*Action of Moving Ice.*

Glaciers.—On high mountains and in high latitudes, as in Greenland or Lapland, the water precipitated from the atmosphere falls as snow instead of rain. This occurs even in the Torrid Zone wherever the land exceeds an altitude of 15,000 or 16,000 feet above the sea, and in all other latitudes at a less height in proportion to their distance from the Torrid Zone. In the Alps the snow-line in summer occurs at a height of 8,000 feet above the sea. Near the North and South Poles it comes down to the level of the sea. In regions of perpetual snow even the hottest summer's sun fails to melt all the snow that falls in a year, hence there is a continual accumulation of it, and, if there were no way of getting rid of it, all the water in the world would be eventually transferred to these regions and remain there in a solid form. There is, however, a drainage from these snow-covered regions by means of glaciers, just as there is a drainage from other regions by means of brooks and rivers. The lower part of all perpetual snow is being constantly converted into ice; the weight of the superincumbent mass forces out the air from between the snow-flakes and binds them together, just as a snowball is made harder by the pressure of the hand; the water, too, which is derived from the melting of the surface by the sun in the daytime, percolates downwards and becomes frozen again below. The ice thus formed, slips and slides down the slopes of the mountain regions, being pressed forward by the weight behind, till it is pushed down into the valleys, along which it travels in the form of ice rivers or *glaciers*. The glaciers of the Alps are sometimes as much as 600 feet in depth, and they fill the valleys for many miles below the snow-line, till they come down to a level of about 4,000 feet below it, where they terminate, in consequence of the ice melting into water and proceeding as a brook or a river. In high latitudes, where the snow-line is near the sea-level, the ice is pushed into the sea, and the portions which break off from time to time are floated off as icebergs.

We have seen that in the case of rivers two processes

are going on at the same time, namely, erosion and transportation; the rivers of ice perform the same kind of work, but in a different way. Wherever a glacier passes beneath a crag or cliff of rock it receives on to its surface a continued supply of blocks and stones which are detached by the process of atmospheric weathering, described on p. 79. A line of such rock-fragments may generally be seen at each side of the glacier. Where two glacier streams unite the two lines of transported stones on their adjacent sides come together and form a double median line along the centre of the glacier below the junction of the two valleys. Thus, if a glacier happen to have many important tributaries proceeding from different valleys, and uniting to form one large ice stream, this may come to have many separate lines of stones and rubbish, which are all carried along to the place where the glacier terminates. Here they are all thrown down, and form an irregular mound or pile of rough, angular *débris* mixed with earth, which in Switzerland is called a *moraine*. This term is also applied to the lines of stones on the glacier, so that there are three kinds of moraines, *lateral*, *medial*, and *terminal*.

The surface of a glacier is not always smooth; on the contrary, it is generally rough and broken, and sometimes it is traversed by deep cracks or clefts called crevasses. Many stones and blocks fall down these, others are picked up from the bed of the glacier and get firmly frozen into the ice. The stones thus fixed in the under surface of a glacier scratch and groove and wear away the rocks over which they are moved, and are also scratched and worn themselves by the hard projections of the rocks beneath. One result of this action is the production of a quantity of fine mud and sand, so that if a lump of glacier ice is dissolved in a glass of water, it makes the water as turbid as if a spoonful of milk had been put into it. The river that always springs from the end of a glacier carries away all this mud, and flows as a dirty yellowish or greenish white stream, until it reaches the sea or some great lake, in which the sediment may be deposited.

Another result of this grinding action is the smoothing and polishing of the rock surface below, and the rounding off of all prominences beneath the glacier, so as to leave a

peculiarly moulded outline which is quite different from the surface features produced by any other agency. If we examine a valley where the glacier once extended much further down than it does now, we shall find that the ice has left a smoothened surface of rock, rising here and there into rounded bosses or hummocks, which have a smooth, polished, and gently sloping surface on one side, with a rougher and steeper slope on the other; we shall also notice that the smoother faces of these hummocks all look up the valley towards the quarter whence the moving ice came. When viewed from a distance they have been thought to bear some resemblance to a flock of sheep lying down on the ground, and have hence been called *roches moutonnées*.

Passing down the valley we may also come upon the terminal moraine of the ancient glacier, still remaining as a mound of rubbish and rock *débris* stretching across the valley in a semicircular or horseshoe-shaped curve.

It is not only in countries where glaciers now exist that these ice-marks are found. Many valleys in the north of England, in Scotland, Ireland, and other parts of the world, present the same appearances as those of Switzerland, only the tool-marks are not quite so fresh-looking. The rounded forms of the *roches moutonnées* are, however, just as remarkable, and in some valleys a series of terminal moraines may be found, one above another, showing how the glacier gradually dwindled away, and shrank higher and higher up the valley.

From the above description it is clear that the passage of glacier ice down a valley will scrape out all the soils and superficial deposits that may previously have accumulated in the valley, and will sweep the materials onward to swell its terminal moraine. Any hollows or depressions which may have existed in the valley, and were, perhaps, filled up with alluvial deposits before the glacier was developed, will be cleared out by the ice, and subsequently, when the glacier has disappeared, these hollows will remain as lakes.

It has even been suggested by Sir A. Ramsay that the rock basins in which many lakes lie have actually been excavated by the erosive action of the glaciers; on this

point, however, there is much difference of opinion among geologists, but it is at any rate a noteworthy fact that lakes are most numerous in those countries which are known to have been glaciated in comparatively recent times.

CHAPTER VIII.

MARINE AGENCIES.

ACTION of Waves and Tides.—The upper surface of the sea is kept in continual agitation by the force of the winds, which raise it into waves of all dimensions; these waves roll in upon every exposed coast-line throughout the world, and act as instruments of erosion and destruction.

Twice a day, also, the attraction of the sun and moon lifts the ocean into tides, which become currents as they approach the land. The height of the tides and the force of the currents thus produced depend upon the configuration of the coast. Their effects are greatest where shelving shores and narrow gulfs or bays confine the tidal waters into a narrower space; in such cases the rise and fall of the tide often amounts to 30 or 40 feet. In the Bristol Channel it is more than 40 feet, and the currents are proportionally powerful.

This rise and fall of the tides assists the waves by giving them a greater vertical space upon which to act, and the tidal currents serve also to transport the finer materials which are washed away from the coast. To estimate the power of sea-waves, they must be seen under the influence of a storm or gale of wind. Just as a brook in time of drought furnishes no measure of the work it does in time of flood, so the sea on a calm day gives no idea of the force with which storm waves can break on a rocky shore.

It has been ascertained that the average force of the breakers in winter time on the west coast of Scotland is equal to a pressure of 2,086 lbs. (nearly a ton) on every square foot of rock; during a storm it is greater. Mr. Stevenson found by experiments at the Bell Rock Lighthouse that the pressure was sometimes a ton and a half upon the square foot, and that at Skerryvore in the At-

lantic it was doubly powerful, viz., about three tons to the square foot. At Eddystone Lighthouse the force of the waves in a storm was calculated to be equal to 3,013 lbs. (nearly $1\frac{1}{2}$ tons) on the square foot.

Such a force is evidently capable of dislodging and moving very large fragments of rock, especially if the blocks have been previously loosened by the action of rain and frost. Professor Geikie [1] states that on the coast of the Pentland Firth blocks from 7 to 13 tons in weight had been quarried out of the cliffs at a height of 70 feet above the sea; the waves must have risen to that height, and still have been able to bring down these immense fragments. In other places they have torn up similar masses of rock, and heaped them together at a height of 62 feet.

The damage and destruction which is often wrought upon piers and breakwaters during storms enables us to realize the enormous power of the waves, and anyone who has witnessed the making of a breach in such massive masonry will be better able to appreciate the action of the sea upon coasts and cliffs. During heavy gales at Plymouth in 1824 and 1829, blocks of limestone and granite, weighing from two to five tons, were washed about at the breakwater like pebbles. About 800 tons of such blocks were borne a distance of 200 feet up the inclined plane of the breakwater. In one place a block of limestone, seven tons in weight, was washed a distance of 150 feet.[2] On the coast of Clare, in Ireland, blocks of rock may be seen which have been torn from rock-masses 20 feet above high-water mark, and thrown up on to the grass full 20 feet higher and 20 yards farther back.[3]

The mere blow and force of the wave, however, is not the whole of the force exercised; when the water is dashed against a rock or cliff, some of it is injected into every crack and crevice it can find, and its pressure is exerted in forcing asunder the walls of the fissure. Moreover, the air that was previously in the fissures is suddenly compressed and impelled into the minuter cracks and planes of division. With the recess of the wave the pressure is suddenly

[1] "Scenery and Geology of Scotland," p. 61.
[2] De la Beche's "Geological Observer," p. 47.
[3] Jukes' "Manual of Geology," second edition, p. 220.

relieved, and the air and water rush out with a suction that is capable of loosening and dislodging large blocks of rock. No sooner are such fragments torn away from the cliff than they are immediately converted into engines of further destruction, for they are lifted by the waves and hurled against the rocks, so as to act like hammers or battering rams.

If the larger cracks and fissures run at right angles to the cliff, they form so many lines of weakness, which yield more readily to the continued action of the waves, and a long cave or else an open inlet is gradually formed. In other cases the larger cracks or master joints run parallel to the face of the cliff; shorter and wider cavities are then formed near the base of the cliff, which is thus undermined till one of the main joints is reached, when the unsupported mass above falls in ruin on the shore. The breakers then proceed to reduce the size of the fallen fragments, dashing them one against the other, and breaking them up into pebbles and sand, till at last they are washed away, and the face of the cliff is exposed again to fresh assaults.

Instances of the action of the breakers on jointed rocks are to be seen on all coasts. The hard rocks of the western coast of Ireland afford many illustrative examples of the action as going on at present, their cliffs, caves, and rocky islets having been formed by this action. Mr. Jukes states, on the authority of Mr. W. L. Willson, late of the Geological Survey of Ireland, that in the far part of the promontory between Bantry and Dunmanus Bays there are dark holes in the fields some distance back from the edge of the cliffs, looking down into which the sea might be dimly seen washing backwards and forwards in the narrow cavern below.

"At high water, and during gales of wind, with heavy breakers rolling in upon the coast, vast volumes of water are poured suddenly into these narrow caverns, and rolling on, compress the air at their further end into every joint and pore of the rock above, and then, suddenly receding, suck both air and water back again with such force as now and then to loosen some part of the roof. Working in this way, the sea sometimes gradually forms a passage for itself to the surface above, and if that be not too lofty, forms a 'blow-hole,' or 'puffing-hole,' through which spouts of

foam and spray are occasionally ejected high into the air."[1]

Some of these blow-holes open down into cavernous gullies, which lead from one cove to another, behind bold headlands of even a hundred or more feet in height; showing the commencement of the process by which headlands are converted into islands. One such square precipitous island, near Loop Head, County Clare—which in 1862 was at least 20 yards from the mainland—was said by the farmer who held the ground to have been accessible by a twelve-foot plank when he was a boy.

Formation of Shore Platforms.—The foregoing facts and descriptions demonstrate the powerful action of the sea on the land; we have now to learn the limits which are set to this action.

We have seen that the erosive agents are the waves, not the marine currents, which only arrange the materials obtained by the former. Transportation may, and, doubtless, does go on at considerable depths, and during violent gales it is said that the sea-bottom has been disturbed to a depth of 50 fathoms; but this will only cause a re-arrangement of the sand and mud at the bottom. Currents may also erode channels through these unconsolidated deposits, but can hardly have much effect upon solid rocks.

The action of the waves is usually confined to the space between high and low water mark, and their force is found to be greatest above half-tide level and before the height of the tide. Moreover it is the upper or plunging part of the wave which possesses erosive power, the lower waters being accumulative in their action, first pushing onward and then withdrawing the pebbles of the beach. As the tide recedes from half-tide level, the surges become smaller and smaller, and the backward current stronger, till at low tide the sea is comparatively quiet. Between these points, therefore, a line is reached where the erosive and accumulative actions balance one another, and below which no erosion takes place. This line is always a little above the level of low tide, and may be called the *line of non-erosion*.

On a rocky shore the tendency of these conditions is to

[1] Jukes' "Manual of Geology," second edition, p. 220.

produce a horizontal or gently sloping platform, the outer edge of which corresponds to the line of non-erosion, so that its surface is bare at low water. This platform is often called a *scar*, and its inner side is bounded by cliffs more or less lofty, according to the height of the land which is eaten into. Fig. 26 is a section across such a platform, the line A representing high tide level, and B low tide level. When the land was first brought into the position it here occupies with regard to the sea-level, the line of cliffs stood at E, over the outer edge of the platform, and the waves have slowly cut them back to the point, F.

Recession of Cliffs.—Since the beating of waves on a coast line results in the formation of cliffs, the very presence of a range of cliffs is a proof that the coast is being worn back. The rapidity of this erosion will differ at different points, and depends on various circumstances, partly on

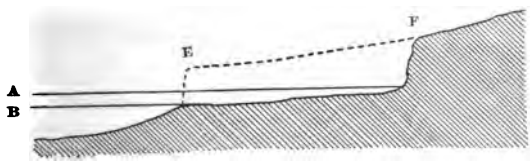

Fig. 26. Formation of a Shore Platform.

the position of the cliff and depth of water at its base, partly on the force of the breakers, and partly on the assistance derived from sub-aërial agencies—rain, frost, and springs—which sometimes work faster than the waves, and cause the cliffs to slope backward at a greater or less angle from the shore. But the most important condition is the relative hardness or resistant power of the rocks themselves.

On the western coasts of Europe the severest storms and strongest gales come from the westward, with winds ranging from S.W. to N.W., and as they sweep over the vast expanse of the Atlantic Ocean they raise up enormous waves which break upon the land with tremendous force. The power of these breakers has already been described, and our western coasts afford many instances of the relative powers of resistance which different rocks possess.

The more yielding strata are worn into deep bays and inlets, while the harder rocks stand out as capes, promontories, and detached islets.

Nowhere is this result so clearly seen as on the south-west coast of Ireland, where beds of indurated sandstone form the bold headlands separating Dingle, Kenmare, Bantry, and Dunmanus Bays, while these inlets are all eroded out of more destructible shales and limestones.

The coasts of Devon and Cornwall present similar examples on a smaller scale, the numerous creeks and coves being all scooped out of some comparatively soft rock, frequently the shaly slate locally known as *killas*, while the harder rocks, such as granite and dolerite, have offered more resistance to the breakers and stand out as headlands and promontories. Polventon Cove, on the east side of Trevose Head, is a natural harbour formed in

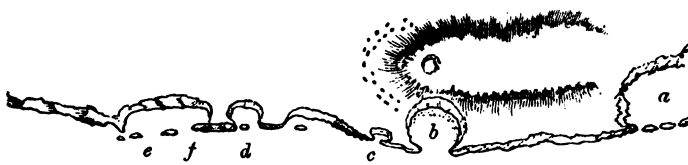

Fig. 27. Part of the Dorsetshire Coast[1] (distance about five miles). *a* = Mupe Cove. *b* = Lulworth Cove. *c* = Stare Cove. *d* = Man-of-War Cove. *e* = Durdle Cove. *f* = Barn Door.

this way and protected from the north-west winds by a jutting ridge of hard, igneous rock (greenstone), which forms an efficient breakwater.[2] The erosion of the shores of Tor Bay has been described by Mr. Pengelly.[3]

In England, however, the most remarkable instances of this selective action of the waves are to be found on the Dorsetshire coast. The cliffs which form this coast consist of a variety of strata, some of which are very much softer and more yielding than the rest. As a consequence, wherever these are brought within the reach of the waves deep recesses, or coves, have been excavated out of them.

[1] This and fig. 28 are taken from Mantell's "Geological Excursions."
[2] See De la Beche's "Geological Observer," p. 51.
[3] "Geologist," vol. iv., p. 447.

Fig. 28. Durdle Cove, from the inland cliff.

No less than six of these coves occur within the distance of five miles, while the intervening portions of the coast line form nearly straight ranges of cliffs. These features are shown in plan in fig. 27, and an idea of the scenery they produce may be obtained from the view of Durdle Cove in fig. 28; the eastern cape of this bay is formed by a projecting crag of hard limestone (Portland stone) through which the waves have worn a wide gap or archway known as the "Barn-door." The western cape consists of chalk, while the inner cliffs consist chiefly of sands and clays, to the presence of which the bay owes its existence.

The Isle of Wight owes its lozenge shape entirely to the relative hardness of the rocks of which it is composed. Through the middle of the island runs a high ridge of chalk, the two ends of which project east and west, and form the promontories known respectively as Culver Point and The Needles (see fig. 29, borrowed from Mantell's "Excursions"). The Culver cliffs are flanked by Sandown and Whitecliff Bays, while Brixton and Alum Bays occupy the same position with regard to the Needles. All these bays have been hollowed out of the softer sands and clays which lie on either side of the chalk ridge; and we may further observe that the deeper hollows of Sandown and Brixton Bays are doubtless due to the fact that their coast-lines waste more rapidly than do those of the more northern bays.

Where the whole coast consists of the softer kinds of rocks, and especially if it is swept by a strong current which can readily carry off the eroded materials, the waste of land is sometimes very rapid, so that all the inhabitants become sensible of it. This is the case for long distances on the eastern and southern coasts of England, and even within the last few centuries the destruction of land has been so great, that the sites of many villages and some considerable towns along the coasts of Yorkshire, Norfolk, Suffolk, Essex, and Kent, are now beneath the sea, which has eaten away the ground on which they once stood.

The following accounts are chiefly taken from Sir Charles Lyell's "Principles of Geology." It should be observed, however, that it is only at certain points along

these coasts that destruction is going on, not along their whole extent. At some places, as will hereafter be mentioned, deposition and accretion are taking place.

Waste of East and South Coasts of England.—*In Yorkshire* the waste is most rapid along the coast of Holderness, between Flamborough Head and Spurn Point at the entrance of the Humber; this tract consists of beds of clay, gravel, and sand, which form low cliffs against which the waves beat, while a strong current sets from the north and carries away the *débris*.

Fig. 29. The Needles, from Headon Hill, looking southward.

"For many years," says Professor Phillips, "the rate at which the cliffs recede from Bridlington to Spurn, a distance of 36 miles, has been found by measurement to equal on an average $2\frac{1}{4}$ yards annually, which upon 36 miles of coast would amount to about 30 acres a year. At this rate the coast, the mean height of which above the sea is about 40 feet, has lost one mile in breadth since the Norman Conquest, and more than two miles since the occupation of York by the Romans." In some places

the loss of land is said to be as much as 5 yards per annum.[1]

The sites of the villages of Auburn, Hartburn, Hyde, and Ravenspur, are now sand-banks dry only at low water, though Ravenspur, where Bolingbroke landed to depose Richard II., was once so large and flourishing a sea-port as to be a rival of Hull.

Norfolk.—At Sherringham, between Weybourn and Cromer, there was in 1829 a depth of 28 feet of water in the harbour (enough to float a frigate) at the very spot where forty-eight years before there stood a cliff 50 feet high, with houses upon it. The site of the old town of Cromer is now in the German Ocean, the inhabitants having continually built inland as the sea gained on them. It is stated by Mr. Redman[2] that during the twenty-three years which elapsed between the Ordnance Survey of 1838 and the year 1861, a portion of the cliff composed of sand and clay between Cromer and Mundesley receded 330 feet, amounting to a mean annual waste of 14 feet; these cliffs are from 250 to 300 feet high, and the amount of material carried away from them every year must, therefore, be enormous.

On the same coast churches, villages, and manors, such as those of Shipden, Wimpwell and Eccles, have one after another disappeared, so that their previous existence is only known from old records.

Suffolk has suffered in a similar manner. Dunwich, now only an inconsiderable village, was once the chief port in the county. It is stated in Doomsday Book that two tracts of land outside the village had been taxed by Edward the Confessor, but had been destroyed in the few years which had elapsed between that time and the Conqueror's Survey. In other later records mention is made of, at one time, a monastery, at another several churches, then the old port, then 400 houses at once, and gradually the gaol, the town-hall, the high roads, then of ancient cemeteries, the coffins of which were for some time

[1] See a paper "On the Encroachments of the Sea from Spurn Point to Flamborough Head," by R. Pickwell, "Proc. Inst. Civ. Eng.," vol. li. p. 191.

[2] "Proc. Inst. Civ. Eng.," vol. xxiii. p. 31.

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exposed in the cliff—all swept away by the devouring sea. It is even said by Ray that old writings make mention of a wood a mile and a half to the east of the town, the site of the wood being, of course, now farther than that in the German Ocean.[1]

Beacon Cliff, near Harwich, has wasted at a very rapid rate; it is about 50 feet high, and consists entirely of clay. Captain Washington ascertained that between the years 1709 and 1756 it had receded a distance of 40 feet; between 1756 and 1804, 80 feet had been swept away, and between 1804 and 1841, no less than 350 feet, showing a rapidly accelerated rate of destruction.

Kent.—The Isle of Sheppey, off the north coast, furnishes another example of the rapid destruction of clay cliffs, which are continually foundering down under the combined attacks of rain-water and sea-waves. An account of the landslips constantly taking place along the north coast of this island has already been given (p. 92), and the sea is chiefly employed in washing away the ruins which fall on the shore. As much as 50 acres of land have been lost in 20 years, and if the present rate of destruction should continue, it is easy to foresee the total destruction of the island.

Still farther east stands the church of Reculver, upon a low cliff of clay and sand; Reculver was a Roman station, and even in Henry VIII.'s time the church was nearly a mile from the sea. The Roman camp was destroyed in 1780 and part of the churchyard in 1804, but, since then, artificial means have been taken to break the force of the waves and to preserve the church as a landmark.[2]

The Goodwin Sands are probably a remnant of Kentish land destroyed by the sea. Borings made in 1817 showed that there was only 15 feet of sand resting on blue clay, below which the chalk was reached. Tradition connects the name with Earl Goodwin (the father of Harold), who died in the year 1053, and whose estates are supposed to have been situated here.

Sussex.—Westward of Hastings there has been much loss of land, and though Pevensey Level, with its border of shingle, has been formed in historical times, yet for more

[1] Lyell's "Principles," tenth edition, vol. i. p. 520.
[2] See Lyell's "Principles," vol. i. p. 523.

than a century the whole shore-line has been giving way, the rate of waste now being between 3 and 7 feet per annum. At Langney Point between the years 1736 (Desmarest's Survey) and 1844 (Ordnance Survey) the sea had advanced more than half a mile. A comparison between the two Surveys above mentioned shows that the coast between Eastbourne and Beachy Head has receded to the extent of more than a quarter of a mile, and in some places as much as 600 yards, the average loss being between 12 and 15 feet per annum[1] (see map, fig. 30). Of the Martello towers constructed here in 1806, four (Nos. 69 to 72) have since been destroyed by the encroachments of the sea, and are now below highwater mark.

At Beachy Head, which is a promontory of hard chalk, the erosion is less rapid, but falls from the cliff are frequent, and the largest landslip of which record remains took place in 1813, when a mass of chalk 300 feet long and about 80 feet wide was precipitated on to the shore.[2] Seven towers of chalk called the Seven Charles formerly stood out from these cliffs, but the last of them, which was known to have withstood the attacks of the sea for more than a century, fell in 1853.[3]

On the highest point between Seaford and Cuckmere there are the remains of an ancient British earthwork, the area of which is said to have been 12 acres. The southern portion of this earthwork has been carried away by the recession of the cliffs, and only 4 or 5 acres now remain within the lines. We may conclude, therefore, that at least 7 acres have been washed away since the time of the Britons.

Between Newhaven and Brighton the average rate of waste is 3 feet per annum, and Mr. H. Willett states that at Aldrington (3 miles west of Brighton) the encroachment of the sea amounted to 270 feet in ten years, or an annual rate of 9 yards, these figures being obtained by actual admeasurement.

[1] Redman, "Proc. Inst. Civil Engineers," vol. xxiii. For the use of this illustration (fig. 30) I am indebted to Rev. H. E. Maddock and Mr. Chambers, of Eastbourne.

[2] Webster, "Trans. Geol. Soc." vol. ii. p. 191.

[3] Chambers' "Guide to Eastbourne."

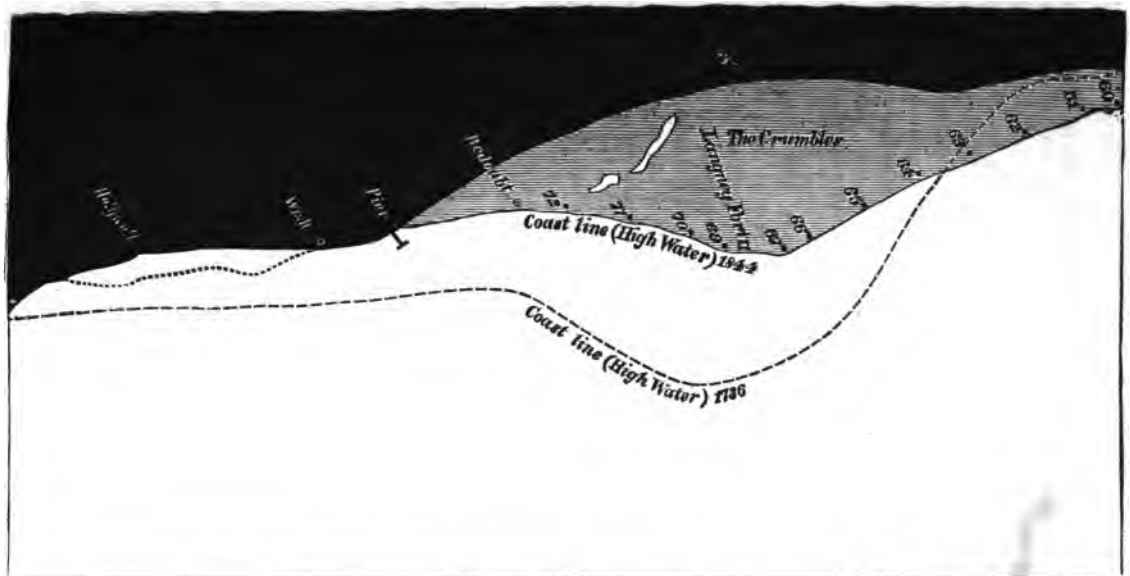

Fig. 30. Changes in the coast-line between Beachy Head and Pevensey.
The shaded parts are land. ● = Martello towers. Scale about one mile to an inch.

Near Worthing, in former times, the sea gained much upon the shore, 70 feet of land at one spot being destroyed in less than a year, but this shore is now protected by groynes. Along the coast from Worthing to Bognor the same tale is told.[1] Between the years 1260 and 1340, a period of only 80 years, no less than 120 acres of land were destroyed in the parishes of Middleton and Felpham, and it is known that half of the former parish has been absorbed by the sea within historical times. The ruins of the church are now on the shore, and the waves carry away bones from the churchyard.

The promontory known as Selsey Bill has likewise suffered great loss. In the time of the historian Bede, A.D. 731, Selsey was a peninsula, and contained 5,220 acres of land; at the present time its area only amounts to 2,880 acres. It was for many years a Bishop's see, and possessed a cathedral and episcopal palace with a large park, which in the time of Henry VIII. was well stocked with deer. Now the site of these buildings is said to be about a mile from the coast, and a small plot called Park Coppice is the only remnant of the park; though the shore and sands are still known locally by the name of the "Bishop's Park."

Hampshire.—The cliffs between Hurst Shingle Bar and Christchurch are likewise worn back at a rapid rate, the destruction being estimated at a yard per annum. Christchurch Head stands out as a promontory, and it is a noteworthy and significant fact that this is the only point between Lymington and Poole Harbour in Dorsetshire where any hard stony masses occur in the cliffs. "Five layers of large ferruginous concretions," says Lyell, "somewhat like the septaria of the London Clay, have occasioned a resistance at this point, to which we may ascribe this headland. In the meantime the waves have cut deeply into the soft sands and loams of Pool Bay, where erosion has been facilitated by the action of springs, causing frequent landslips, and leading to the formation of narrow, short, and deep ravines opening on to the shore, and known locally by the name of chines."[2]

The configuration of the Isle of Wight, and the extent

[1] Dixon's "Geology of Sussex," new edition, p. 73.
[2] "Principles of Geology," tenth edition, vol. i. p. 533.

to which it has suffered from marine erosion, have already been mentioned (see p. 124).

Dorsetshire.—The same phenomena are repeated in the districts of Purbeck and Portland. The manner in which the coves of the Purbeck coast have been formed has already been mentioned; at Portland the erosion has been much more considerable: the cliffs here consist of a soft, shaly clay, overlaid by a massive limestone; the clay is rapidly excavated, so that the cliffs are undermined, and large masses of the superstratum then fall by their own weight. The action of the waves is assisted by that of the springs thrown out beneath the limestone, as in the Isle of Wight, p. 94. Large landslips have often occurred, notably one in 1792, when a tract of ground 1¼ mile long and 600 yards broad was moved towards the sea. The isle of Portland is, in fact, the last remnant of a once extensive tract of land.

Similar destruction and loss of land is going on along the coast between Bridport and Axmouth, the great landslip near the latter place having been already mentioned (p. 95). Near Lyme Regis the rate of waste has been estimated at about three feet per annum.

Coast-ice.—In high latitudes where the shallow water along the coasts is frozen every winter, a particular form of ice comes into play, and constitutes an erosive and detritive agency of no mean importance. During the winter a thick and often broad shelf of ice is gradually formed along the shore, its thickness increasing with every tide, until it sometimes reaches a height of 30 or 40 feet, and its seaward face presents the appearance of a bold wall of ice.

When spring comes, landslips occur, and tons of stones and rock-fragments, loosened by the winter's frost, fall upon the surface of the *ice-foot*, as this shelf is often called. Moreover, the blocks, stones, and shingle which rest on the shore beneath are frozen into the bottom of the ice and become part of its mass. The coast-ice is thus charged with a load of stones and boulders both on its upper and lower surfaces, just in the same way as glacier-ice is, only the quantity of débris is probably greater.

As the thaw proceeds in summer time, this ice-foot is broken up by the waves, and large masses are driven on to

the shore during storms, crushing and grinding the rocks over which they are pushed; other portions are separated from the coast and floated out to sea, forming great rafts or *floes*, each with its load of rock débris.

Even in calmer weather it is clear that coast-ice having numerous fragments of rock fixed in it, and being borne backwards and forwards by the tide, must exercise an enormous grinding and grooving action. Both the stones themselves and the surfaces over which they are moved will be scratched and abraded, and much mud will be produced by the process. It may be observed, also, that a stone fixed in the ice-foot, and scratched along one side by contact with the rock below, may be dropped when the ice begins to thaw, and afterwards ground along its other sides by the stones still fixed in the ice above, so that it may eventually bear scratches all over it, as is the case with so many stones in our Boulder clays.

Speaking of ice-action on the coasts of Grinnell Land, part of North Greenland, Messrs. Fielden and De Rance make the following observations:[1]—"Sea-ice driven on shore by gales, or moving up and down with the tides, is a very potent factor in glaciating rocks and pebbles. Along the shores of the Polar basin this process of glaciating was seen in progress by one of us; and he records in his 'Journal' that at the south end of a small island in Blackcliff Bay (lat. 82° 30 N.), the bottom of the ice hummocks, some 8 to 15 feet thick, were studded with hard limestone pebbles, which were rounded and scratched as distinctly as others taken from moraines; when extracted from the ice, only the exposed surfaces, as a rule, were glaciated. As the tide recedes the hummocks do not always arrive at a position of rest without some disturbances of the subjacent material, particularly on a shelving shore, and the sliding of the hummock to a lower level, and the sound following on the grating together of the pebbles beneath may be noted. In many places where gaps occurred in the lines of ancient sea-terraces, the basement rock, as well as some of the pebbles in the terraces, were found to be glaciated, and there can be no doubt that this

[1] "Quart. Journ. Geol. Soc." vol. xxxiv. p. 566.

is due to the action of shore-ice, the condition of the terraces precluding the idea that it might have been the result of glacier action."

An illustration of the action of such ice on a shelving shore in a much lower latitude is mentioned by Dr. Forchhammer,[1] who states that during a hard frost in February, 1844, sheets of ice were formed in the Sound between Sweden and Zealand, and some of these were driven by a storm into the Bay of Täarbejik, and forced up on the beach, forming a mound more than 16 feet high. When he visited the spot next day, he saw "ridges of ice, sand, and pebbles, not only on the shore, but extending far out into the bottom of the sea, showing how greatly its bed had been changed, and how easily, where it is composed of rock, it may be furrowed and streaked by stones firmly fixed in the moving ice."

To the action of such masses, but still more to that of ground-ice which forms on shallow bottoms, and contains stones frozen into its under surface, Professor Forchhammer attributes the striation of the rocky surfaces round the shores of the Baltic.

When to the ordinary action of tides and winds is added the impact of some of the large masses of ice, which are set loose from the Arctic regions in summer time, and are often driven on to the more southern coasts, still greater results are produced. The action of this pack-ice on a shelving shore is thus described by Professor Milne:[2]— "When we reflect upon the immense mass in one of these moving fields of ice, we can hardly conceive the energy that is stored within it. Everything has to give way before it; and the coast-ice, with its set of gravers firmly bedded in its base, is pushed high and dry, sometimes as much as 100 yards back from high-water mark. It is in this way, by the coming-in of the northern pack, the rise and fall of the tide, and other causes, that the land-ice is driven ashore, and many of the scratches and grooves so common round the coast of Newfoundland have been made."

The impact of this floe-ice seems also to have a rounding

[1] "Bull. Soc. Géol. de France, 1847," tom iv. p. 1182.
[2] "Geological Magazine," Dec. 2, vol. iii. p. 405.

and moulding effect upon such islands and prominences of rock as are exposed to its force, producing forms which, on a large scale, resemble the *roches-moutonnées* formed by glaciers. Professor Milne instances a small islet called Funk Island, near Newfoundland, which is situated directly in the course of the ice-floes coming southward from Baffin's Bay and Labrador. "The northern end of this island, which has every year to face the pressure of the vast fields of ice which are borne down upon it, is visibly worn down, and covered with erratic boulders, whilst the opposite extremity is a low but abrupt cliff."

He argues, therefore, that much of the stratching and modelling which has hitherto been referred to the action of enormous glaciers, may have been produced by the agency of coast-ice and floe-ice acting on the surface of the country during its last slow emergence from the sea.

Sir George Nares observed,[1] that the sea-face of Cape Rawson (Grinnell Land), up to a height of 200 feet above the present sea-level, had been ground smooth by the pressure of the floe-bergs and the ice-foot, the scored and rounded surfaces having remained unimpaired during the gradual elevation of the land to the height mentioned. He also measured a stranded floe-berg forced up on its side. "It was 120 feet long by 103 feet broad, and 80 feet in depth, the highest part being 63 feet above the water-line. It was, consequently, about 25,000 tons in weight, a cubic foot of ice weighing 55·5 lbs. Although this floe-berg was the highest out of the water, it was by no means the largest in our neighbourhood." In some places, such blocks were forced up on the inclined shore, until a rampart-like barrier of solid ice-blocks was accumulated, measuring about 200 yards in breadth, and rising 50 feet high. The erosive force exercised by such an enormous mass can be readily conceived.

The part taken by these ice-floes in transporting and depositing material will be described on a future page.

Influence of Earth Movements on the Rate of Erosion.—If the land continued stationary for a sufficient length of time, it would be ultimately all worn away,

[1] "Voyage to the Polar Sea," vol. i. p. 276.

leaving only a submarine flat or plain, covered by a shallow sea. Some of our present plains and table-lands have been produced in this way, the mountains that once stood over them having been removed by the erosion of the sea. The destruction of Graham's Island in the Mediterranean, and the shallow flat left in its place, illustrate this result.

It has been shown, however (Chapter IV.), that the land is anything but stationary, and that every part of it is liable to be moved upwards or downwards through the upper surface of the sea. During such movements, the waves will, of course, act upon every contour line that is successively brought within their influence. Mr. Jukes has compared the external action of the sea to that of a fixed engine with a horizontal planing and graving machinery, contrived to carve into any substance, while the earth-movements are forces acting vertically, raising or lowering the substance through the horizontal cutting plane.

If the land is elevated, the formation of cliffs is, in many cases, checked, because their base is raised above the reach of the breakers, and a more sloping beach is produced, on which they cannot act with the same power.

If, on the contrary, the land is depressed, the height of the cliffs is diminished, and the erosive action of the waves being thereby accelerated, they eat farther and farther into the land.

It will be instructive to consider a special case of depression, where the land, after having stood at a certain level for a long period has been permanently lowered, and then allowed to remain stationary again for a considerable time.

It is evident that, during the second period of rest, the waves will carve out a second platform, at a higher level than the old one formed during the first period.

Fig. 31 is intended to illustrate the result of this process. The line, A B, indicates the level of high tide during the first period, when the platform between B and D was formed. Depression of the land then caused the sea to flow over this platform, till its high-tide level corresponded with the line C D. The waves continued to cut down the cliffs which once stood over D; but the line of non-erosion being now at a higher level, they could not wear down the

new platform to the plane of the older one, which, therefore, remains as a submarine terrace, until it is covered and concealed by newly-formed deposits.

The Isle of Wight may be cited as an instance of an island standing upon a platform of this kind, produced by the combined effect of subsidence and marine erosion. The island lies entirely within the line of 10 fathom-soundings, so that an elevation of only 60 feet would unite it to the coast of Hampshire, leaving a level platform, with raised beaches all round the present shore of the island. We may, therefore, assume that its cliffs once stood at the outer edge of this platform, and were continuous with those of Hampshire and Sussex, and that they have been gradually cut back to their present position by the erosive action of the sea.

There is good reason, moreover, for believing that this

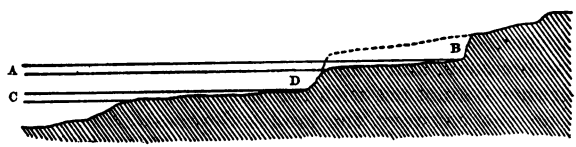

Fig. 31. Erosion increased by Depression.

amount of erosion does not represent the total loss of land which has taken place on the south side of the island in comparatively recent times. There are, at any rate, certain peculiarities in the courses of the rivers, which suggest that when the present system of drainage was established, large areas of land existed over the sites of Brixton and Sandown Bays. Mr. Codrington has pointed out that the short streams which flow into these bays must once have had much longer courses, and were probably tributaries of two large rivers which ran northward into the Solent (see map). He thus accounts for the remarkable fact that both the Yar at Freshwater and the Sandham branch of the Brading river rise close behind the present beach, below high-water mark, and flow northward through the chalk hills. Consequently, he supposes that the present short streams are merely the abbreviated remnants of much larger rivers, the

drainage basins of which have been entirely destroyed by the continual encroachments of the sea.[1]

An instance on a larger scale is furnished by the great submarine platform on which the British Islands themselves stand. It is a well-known fact that the seas surrounding our islands are comparatively shallow, and nearly everywhere less than 100 fathoms deep. The 100 fathom line, in fact, starts from the Bay of Biscay, and passes outside Ireland, at a distance of about 50 miles from its western coast, thence it trends north-eastward, outside the Hebrides and the Shetland Islands, curving in between the latter and the coast of Norway, where a deep channel leads southward and eastward to the entrance of the Baltic Sea.

Outside these limits the sea-bottom plunges rapidly down to the 500 and 1,000 fathom lines, and it is therefore supposed that the European continent formerly had a greater westerly extension as far as the boundary of this submarine platform. If now upheaved it would form an undulating plateau, like a Siberian steppe, only diversified by occasional lakes on the sites of the deeper holes which now exist on the sea-bottom.

The proofs of submergence round the British Isles have already been mentioned (Chapter IV.), and we have only to remember that during the whole period of this recent subsidence, the sea was eating its way farther and farther across the land as it sank, planing down its prominences and filling up its hollows until the movement ceased and the present configuration of land and water was produced.

Dr. Ch. Barrois has described an *elevated* platform of the same kind on the north coast of Spain, formed at a period when the level of that coast was much lower than it is now. He says:[2]—"The rocks of the whole Cantabrian coast, from Galicia to Santander, form rugged mountains, which rise like cliffs at a distance of 3 or 4 kilometres (2 to 2½ miles) from the coast-line, while the space between the sea and these mountains is a narrow plain; the beds being levelled as if a coast road had been pur-

[1] "Quart. Journ. Geol. Soc." vol. xxvi. p. 528.

[2] "Récherches sur les Terrains Anciens des Asturies et de la Galice," "Mem. Soc. Géol. du Nord." tom ii. p. 619.

posely constructed along the base of the mountains." "The altitude of this plain or platform appears to be about 200 feet above the sea, but the tracts formed of sandstone are more elevated than those of limestone, and the latter are higher than the tracts of schist. The numerous torrents which descend from the mountains cut directly across the plain, and give rise to the formation of a great number of transverse sections. . . . The comparison of this plain with the shore platform now in process of formation shows the resemblance between them: the denuded surface which forms a broad terrace along the Cantabrian shore, is nothing but an elevated marine platform, a typical example of the plains of marine denudation described by Professor Ramsay."

Marine Erosion compared with Subaërial Detrition.—In any comparison between the relative amount of erosion performed by the sea, and that accomplished by the other detritive agencies at work upon the surface of the land, the above considerations must be borne in mind.

At the present time where the land is stationary or rising, the sea can only act on the edge of the land, so that the extent of marine erosion must be comparatively small as compared with that effected by the subaërial agencies which act upon every foot of its surface. Dr. Geikie has calculated that if the sea eats away the edge of a continent at the rate of 10 feet in a century; and subaërial agents remove a layer one foot thick from its general surface in 6,000 years, the whole continent of Europe would be entirely worn away by the latter agencies before the sea could pare off more than a mere marginal strip of land 150 miles in breadth.

But, as he truly says,[1] "In estimating the amount of influence to be attributed to each of the denuding agents in past times, we require to take into account the complicated effects which would arise from the upheaval or depression of the earth's crust. If frequent risings of the land or elevations of the sea-floor into land had not taken place in the geological past, no great thickness of stratified rocks

[1] Geikie, "Text Book of Geology," third edition, p. 448.

could have been formed, for the first continents must soon have been washed away." It also follows that the areas upheaved must have been more considerable than the areas depressed, and therefore, even in past times, the amount of detrition effected by rain, frost, springs and rivers, must have always been greater than that accomplished by the sea.

It has lately been pointed out that in early geological times the rise and fall of the tides was in all probability much greater than it is at present. The moon has been gradually increasing its distance from the earth, and when it was much nearer, its tide-producing power will have been greater; and greater tides would enable the waves to act over a greater vertical space. Hence Mr. G. H. Darwin and Dr. Ball[1] conclude that marine erosion must have proceeded at a much more rapid rate than at present, but it is by no means certain that such a conclusion is warranted by the facts. We have seen that marine erosion results in the formation of cliffs, and that its tendency is to cut these cliffs backward till their base is at or near the level of high-water mark. When this has once been accomplished, the rate of erosion is less rapid, and the rise and fall of the tide could make but little difference, since it is only when the waves are beating against the foot of the cliff that active erosion is going on.

If great tides mean great erosion, then we ought to find some evidence of such a result at those places where great tides now exist. The Bay of Fundy (where the tide rises 60 feet) and the Bristol Channel (where it rises 40 feet) are such places, but their shores do not show any signs of excessively violent or rapid erosion. Cliffs exist in both cases at about high-water mark, and below them lies a long stretch of gradually sloping beach. As remarked by Mr. Grenfell,[2] the chief force of the waves is spent in hammering this beach and grinding it into fine sand and mud; so that great tides actually become a source of protection to the land, and are not calculated to increase the rate of marine erosion.

[1] G. H. Darwin, "Phil. Trans." 1879, and Dr. Ball in "Nature," vol. xxvii. p. 201.

[2] See "Nature," vol. xxvii. p. 222.

SECTION II. (*continued*).

B. *Processes of Reconstruction.*

CHAPTER IX.

AT the commencement of Chapter VI. it was stated that in considering the agencies concerned in the continual detrition and renewal of the earth's surface, we should first describe their destructive and erosive effects, reserving all mention of their transportive and reconstructive effects to a future section. Accordingly we now proceed to give some account of the manner in which new deposits are formed out of the materials obtained by the several agencies already described, and to indicate the nature of the formations thus produced. These may be divided into four classes, according to the conditions under which they have been accumulated, each except the second being subdivided into three groups according as they owe their formation to mechanical agencies, to chemical action, or the growth of organic matter. The deposits formed by rivers and glaciers, however, are all the result of mechanical action.

This classification is set out in the following table:—

Terrestrial	Rain, frost, and wind .	Mechanical.
	Springs and percolating water	Chemical.
	Worms and plants . .	Organic.
Fluviatile	Rivers	Mechanical.
	Glaciers	
Lacustrine	Subsiding sediment. .	Mechanical.
	Evaporation of water .	Chemical.
	Animal agency . . .	Organic.
	Vegetable agency . . .	
Marine	Subsiding sediment . .	Mechanical.
	Action of sea-ice . . .	
	Evaporation of water .	Chemical.
	Animal agency . . .	Organic.

TERRESTRIAL DEPOSITS.

§ 1.—*Mechanically formed.*

1. Soil, Rain-wash, Brick-earth, &c.—It was shown in Chapter V. that the heat of the sun, the fall of rain, and the freezing of water exercise a powerful effect upon the surface of all rocks at or near the surface of the earth, and lead to their gradual decay and disintegration.

In temperate and humid climates rain is by far the most potent of these agencies; acting in the first place chemically by means of the oxygen and carbonic acid which it contains, it decomposes and dissolves some of the constituents of the rocks exposed to its influence, and so loosens the coherence of their constituent particles that they are rendered soft and crumbling to a greater or less depth from the surface. This rotten and decomposed portion of the rock is then subjected to still further disintegration by the mechanical action of the falling drops of rain, and the lighter particles are eventually washed away by the rills into which the rain-drops collect, while the residue remains to form the soil of the district.

The various kinds of soil which mantle the earth's surface, and conceal the underlying rock or subsoil, have been primarily produced in this way, the formative action being assisted, as we shall presently see, by the agency of plants and earth-worms. The nature of the soil, therefore, depends largely upon the character of the rock beneath, and is heavy or light according as argillaceous or arenaceous matter preponderates in the rock from which it has been formed. Its quantity, too, depends partly on the kind of rock acted upon, its capacity or incapacity of resisting disintegrating agents, and partly upon the contour and slope of the ground.

It has been ascertained that the soil has everywhere a tendency to descend from higher to lower levels: wherever there is a slope the soil is bodily but slowly travelling from the top to the bottom, and the steeper the slope the more rapid is the motion; so that in valleys and *bottoms* where it is not carried away by streams, considerable deposits of *rain-wash* or *brick-earth* are gradually accumulated.

If a trench is cut down the side of one of our English valleys, it will be found that on the upper slopes the soil is thin, and the subsoil may perhaps be within six inches of the surface, while lower down it will be concealed by 5 or 6 feet of accumulated rain-wash. In some valleys such rain-wash is thick enough to be dug for brick-earth.

Dr. Darwin made some interesting experiments with the view of estimating the average rate at which the soil moves,[1] and he found that on a grass-covered slope with an inclination of 9½ degrees, 2·4 cubic inches of earth (weighing 1·85 oz. whilst damp), annually crossed a line measuring one yard in length. "This amount," as he says, "is small, but we should bear in mind how many branching valleys intersect most countries, the whole length of which must be very great, and that earth is steadily travelling down both turf-covered sides of each valley. For every 100 yards in length in a valley with sides sloping as in the foregoing cases, 480 cubic inches of damp earth, weighing above 23 lbs., will annually reach the bottom. Here a thick bed of alluvium will accumulate, ready to be washed away in the course of centuries, as the stream in the middle meanders from side to side."

The formation of kaolin clay from granite is an excellent instance of the disintegration of a rock and the reconstruction of its materials. The mode in which the felspar of the granite is decomposed, has already been described (p. 71). The silicate of potash is removed in solution by rain-water, and the silicate of alumina is carried away in suspension. The latter when re-deposited in hollows and valleys, forms the valuable beds of kaolin or china-clay, a hydrated silicate of alumina. Such deposits contain grains of quartz, scales of mica, and other impurities, which are separated by washing before the clay is exported to the potteries. Large deposits of kaolin occur in Cornwall and other granitic districts.

In general, however, the insoluble residue remains on the surface of the parent rock, wherever the slopes are not steep, and forms the superficial soil. Thus, some chalk districts in the South of England are covered with a peculiar

[1] "Vegetable Mould and Earth Worms," 1881, p. 269.

soil, called the clay with flints, the formation of which is explained as follows:—White chalk is nearly pure carbonate of lime, the percentage being from 96 to 98, with only 1 or 2 of insoluble matter; but it contains nodules of flint, which are likewise insoluble. The carbonate of lime is slowly, but continually, removed in solution by rain-water, and the insoluble residue gradually accumulates, forming a reddish loamy or clayey soil, full of flints. With this are mingled the remnants of certain loams and clays, which once spread over the chalk downs; and the resulting deposit is in some places several feet thick.

Cave Earth, &c.—When brooks and torrents are engulphed in open fissures and swallow-holes, the earthy materials which they carry along in mechanical suspension are deposited underground, in the hollows of their subterranean channels. Thus the torrents of the Morea, mentioned on p. 90, are usually charged with reddish mud, sand, and pebbles, when they enter the *katavothra*, but are pure and limpid when they flow out again. Inside the caverns are found deposits of red mud, containing pebbles and bones of various animals, which had been washed in during the floods. Similar beds have been found in the caves of Malta and Gibraltar.

In most caverns, pieces of rock are from time to time detached from the roof, and the fragments are then embedded in the deposit forming below. When accumulations of such *angular* blocks are hardened by calcareous infiltrations, the rock is called a *breccia*, to distinguish it from a conglomerate, which contains only *rounded* pebbles. Such breccias are generally formed on the rocky floor of caverns, and are often overlaid by deposits of fine earth and loam, washed in through the cracks and passages communicating with the surface of the ground. These *cave-earths* are often many feet in thickness, and contain the bones of creatures which have inhabited the cave, or have been dragged in by beasts of prey.

Mountain Screes and Breccias.—In hilly and rocky districts, the materials accumulated by the action of rain and frost are much coarser than ordinary soils, and form deposits of angular gravel, which, in limestone regions, is frequently converted into breccia.

Among the chalk downs of England there are many valleys which are never permanently occupied by running water, but which, nevertheless, contain gravelly deposits, composed of angular flints and stones, mixed with sand. Some of these materials have been swept down by occasional floods of rain, others have rolled down the sides of the valley, or have gradually travelled downwards with the soil.

In mountain districts every steep slope, or cliff has its talus of fallen fragments produced by the agencies mentioned on p. 67. They are frequently of great length and breadth, and good examples may be seen in the hill districts of England and Scotland, where they are called *screes*. The enormous accumulations of débris among the Rocky Mountains forming talus slopes 4,000 feet long, and 1,000 feet thick, have already been mentioned (p. 80).

In North Carolina, U.S.A., there are extensive spreads of angular débris, which have been described by Mr. W. C. Kerr. Some of the rock-fragments of which they are composed have travelled a distance of 6 miles from their parent sites, and now occur at the bases, or on the lower slopes of the mountains whence they have been derived. "They have crept down the declivities of the hills, exactly as a glacier descends an Alpine valley, by successive freezing and thawing of the whole water-saturated mass, both the expansion of freezing and gravitation contributing to the downward movement."[1] Snow also falling on such talus-slopes, and melting in the summer, would assist in giving motion to the mass.

Sir A. Ramsay accounts for the formation of the limestone breccias of Gibraltar in the same way.[2] These consist of "an accumulation of angular blocks of limestone embedded in a matrix of calcareous grit and earth, the whole forming a rock-mass as solid as the Gibraltar limestone itself. It varies in thickness from a few feet up to 30 or 40 yards. Sir Charles Lyell observed a breccia in the course of formation at the pass of Escrinet, near Aubenas, in France.[3] "Small pieces of disintegrating limestone are

[1] "Report of the Geol. Survey of North Carolina," vol. i. p. 156.
[2] "Quart. Journ. Geol. Soc." vol. xxxiv. 1878, p. 505.
[3] "Principles of Geology," tenth edition, vol. ii. p. 522.

transported, during heavy rains, by a streamlet, to the foot of the declivity, where landshells are very abundant. The shells and pieces of stone soon become cemented together by stalagmite into a compact mass, and the talus thus formed is in one place 50 feet deep, and 500 yards wide. So firmly is the lowest portion consolidated, that it is quarried for millstones."

Under certain conditions, when a coast line has been elevated the angular fragments and débris of all sizes which have fallen from the cliffs and slopes, accumulate on the ground beneath, and sometimes form deposits from twenty to thirty feet in thickness. In Devon and Cornwall these accumulations are known by the name of "head."

In the Falkland Islands the rock fragments which are detached from the hill sides travel down the slopes and accumulate in the valley bottoms to such an extent, that they form veritable "stone-rivers," which continue to move slowly and gradually down the valleys till they terminate in the sea after the manner of a glacier. The blocks are derived from certain bands of a hard rock, called *quartzite*, which are exposed along the sides of the hills and ridges; every little glen contributes its stream of angular fragments to swell the volume of that in the main valley.

The movement appears to be due partly to the action of the trickling rain-water, which flows among and below the stream of blocks, and partly to the effects of alternate expansion and contraction of the blocks themselves. When a stone resting on a slope is heated by the sun, its greatest expansion is in the direction of least resistance, that is along the downward side, or edge; again, when cooled at night, its own weight prevents it from contracting so much upwards from the bottom as downwards from the top; both forces, therefore, tend to cause a slight downward movement of the whole mass.

Blown Sand.—The sands blown off the shore by the wind drift into ridges and undulating tracts, called *dunes*, which often spread over considerable areas. On many shores these drifts continually advance inland and cover up fertile districts with barren sand; in other places the dunes form a bar across the mouth of some estuary and

cause the accumulation of silt inside which may eventually become habitable land.

As an instance of the former effect, the sand-drifts of the north coast of Cornwall may be cited; these have invaded a considerable area of cultivated land, and now form hills several hundred feet above the sea-level. This sand is largely composed of comminuted shells, and some parts of it are being converted into stone by the infiltration of carbonate of lime and oxide of iron.

Along the shores of the Bay of Biscay the sands used to advance inland at the rate of 60 or 70 feet per annum, overwhelming houses and farms in their progress, but this has been arrested by the planting of pine forests.

Accumulations of blown sand are frequent on the coasts of Australia. Mr. Jukes[1] describes an instance on the eastern coast near Port Bowen, where large sandbanks are exposed at low water. "These dry rapidly under the hot sun and the trade-wind, which blows home upon the shore, then drifts the sand up upon the beach, and piles it into hills 50 or 60 feet high. Behind these hills is a large mangrove swamp, which is being gradually buried under the advancing sand . . . Large districts, with hills of 200 or 300 feet in height, are found also on the coasts of Western Australia, stretching sometimes ten miles inland, formed of loose incoherent sand, once apparently drifted by the wind, though now brought to rest by the growth of a wide-spread forest of gum-trees. Parts of these sands, which consist greatly of grains of shells and corals, are compacted together into a stone, hard enough to be used for building, by the action of the rain-water dissolving some of the carbonate of lime, and re-depositing it on evaporation. Curious cylindrical stems, from 1 inch to 18 inches in diameter are there seen projecting from the soil, and have been taken for petrified trees, which they greatly resemble; but I believe them to have a stalactitic origin, due to the percolation of water down particular pipes and channels in the sands."

Tracts of blown sand, however, are not confined to the vicinity of sea-shores; they are frequent in the deserts of

[1] Jukes' "Manual of Geology," second edition, pp. 154, 155.

Africa and Arabia, where they are formed from the disintegration of sandstones and arenaceous limestones. Many of the ancient temples of Egypt have been buried under drifts of sand, and the whole Egyptian valley would, doubtless, have been overwhelmed by the desert-sands if it had not been for the annual flooding of the country by the Nile. In Southern India, in the district of Tinnevelly, a sand-drift is described as advancing in a progressive wave and overwhelming fields and villages in its course. These sand-hills are being gradually driven from W.N.W. to E.S.E., that being the direction of the prevailing winds in the regions where they are situated. A comparison between surveyor's marks, fixed at various times since the year 1808, shows that the whole mass of hills is moving E.S.E. at the rate of about 51 feet a year. Efforts to arrest the drift, by planting trees, grass, and creepers, have as yet proved unavailing.

§ 2. *Chemically-Formed Deposits.*

Mineral Matter in Solution.—We have seen that all percolating water is able to dissolve certain portions of the rocks through which it makes its way, and to hold these substances in solution until it is evaporated.

Carbonate of lime is the substance which is most frequently and most abundantly dissolved by water; it is present in all spring and river waters, and when the quantity of it is large it produces the quality popularly known as *hardness*. Many springs, however, contain other mineral compounds, or salts, in solution; of these the most frequent and important are Carbonate of Iron, Carbonate of Magnesia, Sulphate of Lime (Gypsum), Sulphate of Magnesia (Epsom Salts), and Chloride of Sodium (Common Salt).

Waters which rise from great depths, or which traverse heated rocks in volcanic districts, acquire a high temperature, and are then able to dissolve silica and other less soluble matters; moreover, the presence of alkaline carbonates (*i.e.*, those of Soda and Potash) facilitates the solution of silica, and enables the water to hold a larger quantity of it in solution.

The amount of material thus abstracted from the rocks and carried away in solution is very great, as will appear from simple calculations based on the analyses of the waters of various springs. Two instances will suffice: (1) Bischoff says that there are fifty springs near Carlsbad, giving out 800,000 cubic feet of water in twenty-four hours, from which a mass of stone weighing 200,000 lbs. could be deposited in that time. Carlsbad itself is built upon a mass of peculiar calcareous rock deposited by these springs, and known locally by the name of Strudelstein; the whole valley is, in fact, filled up with similar deposits. (2) The Bath wells yield 181,440 gallons a day, and each gallon contains 144 grains of mineral matter in solution, which is equal to 3,732 lbs. per day, or 608 tons in a year. From these figures Professor Ramsay has calculated that if the mineral contents could be precipitated and solidified into a rock like limestone, the amount annually discharged would form a column 3 feet square and about 912 feet high.

Deposition of Salts in Solution.—When water containing carbonate of lime or other salts in solution is exposed to evaporation, each drop loses both water and carbonic acid, and becomes gradually saturated with the mineral matter, till it can no longer hold it in solution. Consequently, if the evaporation is continued beyond this saturation point, some of the dissolved carbonate must be deposited in a solid form on the surface over which the water is passing at the time, or on to which it is dripping.

Stalactite and Stalagmite.—Drops of water hanging from the roof of a limestone cavern are often coated over with a delicate film of carbonate of lime, like the finest tissue-paper. This gradually forms a little tube, which may be seen sometimes to acquire a length of some inches, still retaining all its fragility, until water trickling down the outside of it, strengthens it by the addition of successive external coats. Ultimately such tubes will form long icicle-like pendants, which are called Stalactites and grow downward, while the drops which fall upon the floor result in an upward growth, called Stalagmite; and if the two ultimately unite a solid column of crystalline rock is produced. The name stalagmite is also applied to the sheets

of the same material which are formed upon the sides and floor of the cavern; these often alternate with layers of earth and sand brought down by underground waters, so that the cavern is half-filled with deposits of various kinds. The following beds, numbered from below upwards, were found to exist in Kent's Hole near Torquay:—

5. Black Mould at surface.
4. Granular Stalagmite.
3. Cave earth.
2. Crystalline Stalagmite.
1. Breccia of rock fragments.

Travertine.—Some springs are so saturated with carbonate of lime that as soon as they issue into the air they deposit layers of limestone, which is called Travertine or Tiburstone. Striking examples of such deposits occur at the Baths of San Vignone and San Filippo in Tuscany.[1] At the former place a large mass of travertine descends the hill whence the spring issues, and extends for the distance of more than half a mile. One stratum of it is 15 feet thick, and is so compact that it serves as an excellent building stone. At San Filippo the water which supplies the baths falls into a pond where it has been known to deposit a solid mass 30 feet thick in about 20 years. The mass which descends the hill here is a mile and a quarter in length, a third of a mile in breadth, and in some places attains a thickness of 250 feet. This deposit is abruptly cut off by a small stream which carries much away in solution to be utilized or deposited elsewhere.

Gypsum,—Sulphate of lime is also deposited from some thermal waters. Certain springs in Iceland contain numerous sulphates in solution which have all been obtained from the decomposition of the volcanic tuff in the neighbourhood by the acids dissolved in the water.

Professor Bunsen found that if this tuff was pulverized and digested for a time in hot carbonated water, nearly all the constituents were dissolved in the form of bi-carbonates, the solution containing silicic acid, and the carbonates of lime, magnesia, soda, and potash, while the insoluble residue consisted of alumina and oxide of iron. If, however, the

[1] Lyell's "Principles of Geology," tenth edition, vol. i. p. 400.

water was saturated with sulphuretted hydrogen, sulphides were formed, all being dissolved except the sulphide of iron. In hydrochloric and sulphurous acids all the constituents were dissolved.

Hence we see that various salts may be formed in such thermal waters according to the proportion of different gases with which they are impregnated. The formation of sulphuric acid, by the oxidation of sulphurous acid in contact with oxide of iron, would convert the salts into sulphates, and this probably takes place in the Icelandic waters. The sulphates in solution are principally those of lime and magnesia, with smaller quantities of the sulphates of alumina, soda, potash, and ammonia. On evaporation the sulphate of lime is deposited and forms floor-like layers of fibrous, sparry, material, like the beds of gypsum so often met with in England. Beds of clay, often variegated with different colours, are also formed from the decomposition of the tuff.

Siliceous Sinter.—Other thermal springs contain a large quantity of silica in solution, which is deposited as the water cools and evaporates, forming layers and incrustations of hard siliceous stone called Sinter. Deposits of this kind occur near the Geysers in Iceland. Analyses of the water of the Great Geyser show that the amount of solid matter in solution is about 12 parts in 10,000 of water, nearly half of this being silica.

The following are the analyses of Sandberger (1) and Damour (2) :—

	No. 1.	No. 2.
Silica	5·097	5·190
Carbonate of soda	1·939	2·567
Carbonate of ammonia	0·083	—
Sulphate of soda	1·070	1·342
Sulphate of potash	0·475	0·180
Sulphate of magnesia	0·042	0·091
Chloride of sodium	2·521	2·379
Sulphide of sodium	0·088	0·088
Carbonic acid	0·557	0·468
	11·872	12·305

Referring to these analyses, Professor Bunsen remarks

that the silica is dissolved out of the felspathic lavas below and is held in solution as a hydrate by the alkaline carbonates and sulphates. He observes that "no trace of silica is precipitated on the cooling of the water, and it is only after the evaporation of the water that silica is deposited as a thin film on the moistened sides of the vessel, where evaporation to dryness takes place, whilst the fluid itself is not rendered turbid by hydrated silica until the process of concentration is far advanced.[1]" The result of this is that the incrustations increase in proportion as the surface of evaporation expands with the spread of the water. Extensive deposits are thus formed, one such being reported as 16 miles long, 2 furlongs wide, and 100 feet thick.

Geysers also occur in New Zealand, and one near the lake of Rotomahana, forms beautiful terraces of sinter, which have been described by the Rev. R. Abbaye.[2] The Geyser from which the water issues is situated on the border of the lake, and a hundred feet above its level; on the intervening slope the descending waters have deposited their silica and have formed a series of terrace-basins. These basins are mostly semicircular in shape, but vary much in size, some only occupying the space of a few square feet, others extending for a length of 20 or 30 yards. The sinter itself contains about 97 per cent. of hydrated silica, so that it is nearly a pure siliceous deposit.

The most wonderful exhibition of the phenomena connected with Geysers is to be found in the Great Geyser basin of the Firehole River in the Yellowstone Park, United States; Dr. F. V. Hayden thus describes the scene:[3]—"Ascending the Firehole, we find the surface on both sides the river covered with a thick siliceous crust, and completely riddled with springs of every variety. Quiet springs, with basins varying from a few inches to a hundred feet in diameter, are distributed everywhere. Some high pyramidal cones, with steam issuing from the summits, indicate the last stages of what were once important Geysers." Professor Geikie, in writing of this

[1] De la Beche's "Geological Observer," p. 374.
[2] "Quart. Journ. Geol. Soc." vol. xxxiv. p. 170.
[3] "Amer. Journ. Science and Arts," 1872, p. 161.

region says: "A prodigious mass of sinter has been laid down, and the form of the ground has been thereby materially changed. We made some short excursions into the forest, and as far as we penetrated the same floor of sinter was everywhere traceable." Another interesting feature of the region is the quantity of incrusted and silicified wood found scattered about the springs.

In the Grand Cañon of the Yellowstone immense deposits of silica, coloured every shade of red, yellow, and white, are seen to rest upon the irregular surface of an old lava-stream. The remarkable beauty of this valley is largely due to the exquisite delicacy and variety of these colours.

§ 3. *Deposits organically formed.*

Soil or Mould.—The mode in which ordinary soil or mould is formed, has already been described; its dark colour is due to the presence of decayed vegetable matter, but the quantity of this in ordinary soil or field earth is very small. In what is sometimes called vegetable mould the amount is greater. In one sample of fertile mould the amount of organic matter was ascertained to be only 1·76 per cent., in some artificially prepared soil it was as much as 5·5 per cent., and in the famous black soil of Russia from 5 to even 12 per cent.[1]

Dr. Darwin has shown that earth worms are largely concerned in the preparation of ordinary mould. In making their burrows they swallow the earth and pass it through their bodies, and he observes that the particles of the softer rocks suffer some amount of mechanical trituration in their muscular gizzards, in which small stones serve as millstones.

Dr. Darwin gives several instances in which a layer of earth two-tenths of an inch in thickness per acre has been annually brought to the surface by worms; thus, on good argillaceous pasture-land over the Chalk at Down, the accumulation during twenty-nine years amounted to $6\frac{1}{2}$ inches of mould between the turf and a layer of chalk known to have been spread over the field in 1842. This

[1] Darwin's "Vegetable Mould and Earth Worms," p. 238.

shows a production of mould at the rate of 2·2 inches in ten years.

"The finely levigated castings when brought to the surface in a moist condition, flow during rainy weather down any moderate slope, and the smaller particles are washed far down even a gently-inclined surface. Castings, when dry, often crumble into small pellets, and these are apt to roll down any sloping surface . . . The removal of worm-castings by the above means leads to results which are far from insignificant."[1] (See p. 142.)

Formation of Peat.—In cold and temperate climates, various kinds of plants, which flourish in moist situations, increase and accumulate to such an extent that their decaying remains form large peat bogs or mosses. In England and Europe generally, some species of moss constitute the greater part of the mass, but elsewhere other plants contribute largely to the growth of peat. Mr. Darwin states that in Tierra del Fuego almost all the plants contribute to its production, but especially a plant called *Astelia pumila* (Brown), and it is a singular fact that no mosses enter into the composition of the South American peat. In the English Fen-country the peat is chiefly formed of a moss called *Hypnum fluitans*, but in the mountain bogs of Ireland and Scotland the moss is a species of *Sphagnum*. Excavations in a peat bog show that on the surface grows the green living moss with many other plants. Two or three inches below that is a brown spongy mass, consisting of the fibres of dead plants; this passes gradually down into a compacted brown mass in which the vegetable tissue begins to disappear. Lower down it is still denser and darker, and all obvious traces of fibre and tissue perhaps are lost; until, at a depth of sometimes 30 feet, a compact black substance is found which cuts like cheese, but, except from its dampness, might be called soft coal.

The trunks and branches of trees are frequently found embedded in peat-mosses, especially near the bottom, where the wood is generally converted into a dark brown or black cheesy substance, soft when first uncovered, but har-

[1] Op. cit. p. 306.

dening on exposure to the air. Such is the nature of the material known as Irish bog-oak. According to Sir J. Rennie, many of the peat mosses in Europe occupy the site of great forests, some of which have been destroyed within historical times. The fallen timber, by obstructing the natural drainage and causing the ground to become wet and marshy, has conduced to the growth of the mosses which produce peat. Thus, we are told, that the overthrow of a forest by storm, about the middle of the seventeenth century, gave rise to a peat-moss near Lochbroom, in Ross-shire, and that in less than half a century after the fall of the trees, the inhabitants dug peat there.[1]

Other peat mosses occupy the sites of silted-up lakes and pools, which have been gradually converted into swamps. Many such swamps owe their origin to the damming up of streams by beavers, so that these industrious animals may really be ranked among geological agents. The authors of the "North-West Passage by Land,"[2] observe that the former operations of beavers in Canada must have been upon a very large scale, for "nearly every stream between the Pembina and the Athabasca, except the large river Macleod, appears to have been destroyed by the agency of these animals. The whole of this region is little else than a succession of pine-swamps separated by narrow ridges of higher ground, and it is a curious question whether that enormous tract of country marked *swampy* on the maps has not been brought to this condition by the work of the beavers, who have thus destroyed by their own labour the streams necessary to their existence." At one place they found a long chain of marshes formed by the damming up of a stream which had ceased to exist, the beaver huts had become grassy mounds on the dry land, and the dam in front was a green and solid bank.

Many peat mosses extend over large tracts of land; one of the mosses near the river Shannon in Ireland is said to be 50 miles long with a breadth of 2 or 3 miles. The Great Dismal Swamp of North America is described by Lyell as an extensive morass 40 miles long from north to south, and 25 miles wide, between the towns of Norfolk, in

[1] Rennie's "Essays on Peat," p. 65.

[2] Lord Milton and Dr. Cheadle, op. cit. pp. 178, 211.

Virginia, and Weldon, in North Carolina. "The surface of the bog is carpeted with mosses and densely covered with ferns and reeds, above which many evergreen shrubs and trees flourish, especially the White Cedar and the deciduous Cypress . . . On the surface lie innumerable trunks of large and tall trees blown down by the winds, while thousands of others are buried at various depths in the mire below. The soil to the depth of 15 feet is formed of organic matter, without any admixture of earth."[1]

Near river mouths large tracts of land sometimes pass into the condition of fens or marshes, parts of which support a growth of peat moss. The Fens of Norfolk and Cambridgeshire, the Lewes Levels, Pevensey Marshes, and parts of Denmark and Holland are examples. The surface peat of the Fen-land varies in thickness from 1 to 18 feet; when it is thick enough to be dug for fuel, the uppermost 10 or 12 inches are seen to be dark brown in colour and consist of an amorphous mass of roots, rushes, and moss; the lower portions are quite black, and are bedded in regular layers, the vegetable structure is more obscure, but the mass seems to consist almost exclusively of moss.[2] In Norfolk and Cambridgeshire alone, an area of more than 500 miles is occupied by peat. Excavations in this Fenland show, moreover, that there have been many periods during which the peat moss grew and flourished, for subterranean beds of peat occur at various depths, as many as five having been found one below the other, separated by deposits of clay or silt; just as coal-seams are separated by beds of clay or sandstone.

Remains of forest trees are abundant both in the surface peat as well as in the subterranean deposits; indeed these relics are so abundant in many places, that it is evident that extensive forests have existed from time to time, and in these localities it may have been the destruction of the forests that gave rise to the formation of peat. The trees which grew in these forests were chiefly oak, elm, birch, yew, willow, and sallow; their roots and stumps are frequently found still in the position of growth, and the

[1] "Principles of Geology," vol. ii. p. 506, and "Travels in N. America," vol. i. p. 143.

[2] Skertchly, "Geology of the Fenland," Mem. Geol. Survey, p. 134.

fallen trunks are often from 40 to 60 feet long. It is remarkable that these trunks almost always lie in one direction, viz., with their tops towards the N.E., as if they had been blown down by winds from the S.W.

We can well imagine that when conditions ceased to be favourable to forest-growth, and the ground became marshy and boggy, the stagnant water and the growth of peat would cause the decay of the trees. Thus enfeebled, they would ultimately yield to the force of storms from the S.W., and falling, "be entombed in the material which, their destroyer in life, became their preserver in death." [1]

Mangrove Swamps.—In tropical countries similar accumulations of vegetable matter exist in the mangrove swamps which are formed along low-lying shores and near the mouths of rivers. The estuary of a tropical river is generally bordered by mangrove swamps, and the trees seem to flourish best where they are within the influence of the tide. At low water the stems are seen to be supported by a tangled mass of branch-like roots, which rise out of a bed of thick, black, unctuous mud; but as the tide rises and spreads over the swamp the roots are concealed and the trees then appear to be growing in the water, presenting a much more picturesque appearance.

Small crabs and other marine creatures inhabit the dark slimy mud or crawl over its surface; oysters fasten themselves to the mangrove roots, and often form huge clusters of many hundreds together; decomposing vegetation is everywhere, and the atmosphere of the swamp is close, damp, and malarious.

The following description of mangroves and their habits is quoted from Captain Nelson's memoir on the Bahamas.[2] "The Mangrove (Rhizophora) seldom grows more than 15 feet in height; the strength and durability of its timber are very great, and from its development of roots and its amphibious habit, it is an important agent in the conversion of swamps and littoral tracts into dry land. There are many species, but the most common in the Bahamas are the yellow and the white mangroves. The yellow mangrove sends out horizontal roots inland, and into the water

[1] Skertchly, op. cit. p. 164.
[2] "Quart. Journ. Geol. Soc." vol. ix. p. 210.

it throws down numerous vertical radicles or branch-like roots (to which a variety of living things soon become fixed); it also throws off bud-plants, which dropping from the surface into the water, float until they attain a mud-bank or rock-head or other congenial point of fixture. The white mangrove throws down no pendants, but on every quarter it throws off roots which penetrate the mud horizontally about six or eight inches under the surface, and send up suckers at every three or four inches of their course. Thus each species by the multiplication of roots and stems becomes an effective agent in the retention and increase of soil, and frequently both combine in their work of encroachment on the water and the formation of land; as is well seen along the N.E. shore of Cunningham Lake."

"In the swampy clay and sand of the Florida coast, the mangroves form dense jungles from five to twenty miles broad, and running up the creeks and inlets. Parts of the West Indian Islands (the N.W. inshore coast of Cuba, for example) are also extensively occupied with them."

Captain Nelson also observes that other and much smaller plants contribute largely to the formation of new land in the Bahamas. "The marshy lands that are gradually taking the place of the creeks and brackish lakes, abound with and may be said at some points to consist largely of a highly calciferous moss-like Conferva, which in concert with mangrove roots, grasses, and other plants consolidates and completes the chalky soil."

CHAPTER X.

FLUVIATILE AND LACUSTRINE DEPOSITS.

§ 1.—*Deposits formed by Rivers and Glaciers.*

TRANSPORTATION of Detritus.—Before describing the mode in which deposits of river-borne detritus are formed, it will be convenient to inquire farther into the manner in which such quantities of material are transported by rivers, and into the circumstances which increase or decrease their transporting power.

In studying the mechanical force of water there are three facts which must be remembered:—

1. *Loss of Weight.*—All earths and stones lose one-third of their weight when suspended in water, consequently the force required for lifting them is only two-thirds of the force necessary to lift them through air.

2. *Shape of the Fragments.*—Rounded pebbles can be rolled along by a current of water which would be quite unable to move flat slabs of the same weight; conversely, flat slabs or flakes would sink more slowly than rounded fragments of the same cubic contents. Flakes of mica might therefore be transported onwards where grains of quartz would sink, though the latter might be lighter than the former.

3. *Velocity of Current.*—As already mentioned (p. 101), the velocity of a stream depends upon the volume of water and the declivity of the channel. An increase in either of these factors quickens the current, and increased velocity means increased power to transport material. We learn from Mr. W. Hopkins that the transportive power of water increases as the sixth power of the velocity of the current. Thus if the velocity is doubled its motive power is increased 64 times; if its velocity is trebled, its motive power is increased 729 times, and so on.

It must also be remembered that besides the detritus mechanically transported by the force of the current, the waters of every river contain a large amount of material in chemical solution, which is at the same time being carried onwards to the sea. The mineral substances which occur in spring water have already been mentioned (p. 147), and these, of course, will also be found in the rivers which are fed by the springs. It is seldom, however, that the substances in solution are deposited in any part of the river bed; such deposits are only found in the lakes into which rivers empty themselves, and where the evaporation is sometimes greater than the supply.

Amount of Transported Matter.—The amount of matter carried down annually by any river can be estimated by examining its waters at different periods and determining their solid contents. In order to make an exact calculation of this matter four things should be known regarding the river:—

1. The mean annual discharge of water.
2. The average amount of mud in suspension.
3. The average amount of coarser débris pushed along the river bottom.
4. The proportion of mineral matter in solution.

These data have not yet been all carefully obtained for any one river, but some of them have been estimated in the case of several rivers, with the following results.

The Mississippi carries down every year about 6,724,000,000 cubic feet of sediment in mechanical suspension, and about 750,000,000 cubic feet more of sand and gravel is rolled along the bottom of its channel, making a total of about 7,474,000,000 cubic feet per annum. This would cover a square mile of ground to a depth of 268 feet. The amount in solution is not known.

The Ganges, according to Everest, carries down an amount of mineral matter equal to 6,368,077,440 cubic feet per annum. Such a mass of matter would cover the space of a square mile to the depth of 225 feet every year, or would raise the whole surface of Ireland 1 foot in 144 years. The amount carried in solution is not known.

The amount of matter carried down by any river in flood is very much greater than when the water is low, but Mr.

Mellard Reade has pointed out that the amount in solution does not vary so much as that in suspension.[1] The Nile when in flood brings down 41 times as much matter in solution as it does during low Nile, but the amount in suspension varies, according to Dr. Letheby, from 4,772 parts per 100,000 at low Nile to 149,157 parts at high Nile, or 31 times as much, the flow of water being also increased about 26 times, so that the total amount brought down at high Nile is about 800 times as much as at low Nile.

In the case of the Danube the smallest delivery of suspended matter per day of twenty-four hours, is stated by Sir C. A. Hartley to be 11,000 tons, the greatest 2,500,000 tons,[2] or a variation of 227 times.

This bears out the statement on p. 103, that the erosive and transportive power of rivers in flood is very much greater than it is at other times.

The following are estimates of the mean average amount of matter, per annum, brought down by the rivers mentioned.

Mississippi.	In suspension =	396,205,357 tons.
	In solution =	unknown.
Danube.[3]	In suspension =	67,760,000 tons.
	In solution =	22,521,434 tons.
	Total	90,281,434 tons.
Rhone.	In suspension =	31,600,000 tons.[4]
	In solution =	8,290,464 tons.
	Total	39,890,464 tons.

The upper section of the river Elbe, according to estimates made at Lobositz near its point of exit from the Bohemian basin, carries 547,140,000 kilogrammes (about

[1] "On Rivers," "Trans. Geol. Assoc. Liverpool," 1882.

[2] Reade, op. cit.

[3] This estimate is taken from Mr. Mellard Reade's "Chemical Denudation."

[4] This is calculated from an estimated discharge of 600,381,800 cubic feet of sediment, and assuming that there are 19 cubic feet of such sediment in the ton.

537,325 tons) of suspended matter, and 622,680,000 kilogrammes (about 607,100 tons) of dissolved matter out of Bohemia every year; but of the latter about 192,000,000 kilogrammes consist of volatile substances, so that the amount of fixed solids in solution is about 423,000 tons.[1]

Deposition of Detritus.—It must be borne in mind that the three processes, erosion, transportation, and deposition are closely connected; each may proceed in close neighbourhood to the other, and the hollow which has been formed by erosion one day, may be filled up with sediment on the next. It is seldom that the exact conditions of equilibrium exist, when the velocity of the stream is sufficient only for the transport of sediment without exercising erosion or permitting deposition. For suppose that at a given time or place, the velocity is just enough to keep the

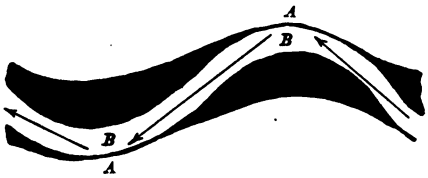

Fig. 32.

load of detritus in suspension, it is clear that a slight rain-shower causing an increase in the volume of water, would at once convert the load into an agent of erosion, while conversely a decrease in the volume would allow some of the load to subside. Speaking generally, therefore, we may say that when the load is not employed in erosion, some of it is being deposited.

A winding river is constantly changing the position of its curves, for the stream is continually eating away the bank on one side of a curve and allowing deposition to take place on the opposite shore. The cause of this is found in the fact that the whole of the water in the stream does not move with the same velocity, and that the line of quickest motion does not keep exactly midway between the banks, but follows the course indicated in fig. 32, the arrows showing

[1] See Geikie, "Text-book of Geology," p. 366.

the impact of the current at the points A, A. Since, therefore, the velocity of the stream is least off the points B, B, and since decreased velocity means decreased power to transport detritus, it follows that deposition will take place opposite B, B, and the angles will gradually be filled up with gravel, sand, or silt, as the case may be.

In the upper part of a river-course where the slopes are steep, and the current swift, only the larger stones are allowed to rest; lower down the valley, where the stream loses some of its velocity, smaller stones and coarse sand are deposited, though much of the latter is still carried onward. Eventually this also subsides, and when a great river reaches the broad plains which are little above the level of the sea, it carries nothing but the finest silt and mud, part of which is deposited, and part is poured into the sea.

Gravel Beds and Alluvial Levels.—When a stream has reached a tract where the lessened slope allows gravel and sand to be deposited, small areas of these deposits are usually found to occur at intervals, first on one side of the river, and then on the other. They are slightly above the flood level of the stream, because, since they were formed, it has deepened its channel and consequently flows on a lower plane than it previously did.

Still lower down, the watercourse itself is generally bordered by strips of level ground, which form a narrow tract or plain, with the stream winding from side to side within it, and over which the waters spread in time of flood. The soil of this flood plain or alluvial level consists partly of earth conveyed by rain down the sides of the valley, and partly of the silt and mud deposited by the overflow of the stream; when the stream is in flood, and overflows this flat and shallow ground, the turbid current is checked, and being unable to carry all its load of sediment, some of it is precipitated to the bottom and remains there on the recession of the waters; this muddy soil is called *alluvium*.

In descending a valley it will always be found that the width of the alluvium increases in proportion as the volume of the stream increases, and within this constantly widening plain, the river pursues a tortuous and meandering

course. At the same time the tracts of gravel increase in size and in height above the river-level, and often form extensive banks and terraces on either side of the alluvium. Not only so, but patches of gravel may be found on the sides of the valley at a still higher level, which are portions of still older gravel beds deposited at a time when the river ran at that level, and before it had cut its channel down to its present depth. These higher banks of gravel have necessarily suffered much from erosion and detrition, and are generally reduced to the state of disconnected patches; but in some cases they are better preserved and remain as more or less continuous terraces, so that the valley side presents a succession of such gravel terraces, and a section across it has the appearance exhibited in fig. 33.

It must not be supposed from this diagram that the

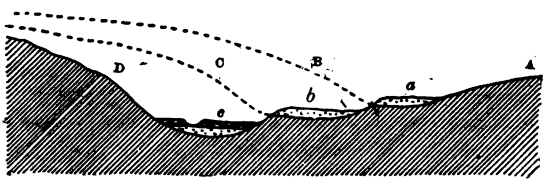

Fig. 33. Terraces of River Gravel.

terrace, *a*, originally extended all across the width of the present valley from A to D. At the time of its formation the valley was both narrower and shallower, its limits lying between A and B, and its western side being indicated by the broken line. As the stream, continually impinging on one bank, cut this side farther and farther back, the valley was both deepened and widened, and the terrace, *b*, remains to testify its extension from A to C. Each bank of gravel was, of course, deposited on the bottom of the valley for the time being, just as the latest gravel, *c*, occupies the bottom of the present valley, and has been deposited since the portion of ground between C and D has been cut away by the erosion of the stream.

The diagram, fig. 33, represents the usual relation of the gravel terraces to the rocky slope below, each terrace being a separate deposit, and quite disconnected from that

above or below. It frequently happens, indeed, that strips of the underlying rock are exposed along the slopes which intervene between the terraces. There are some cases, however, where a section through the valley would present the appearance of fig. 34. Instances occur in North America where the whole country has been depressed since the formation of the great valleys, so that these have been filled up with deposits of sand and clay during the submergence. Subsequent elevation of the land has allowed the rivers to cut new channels through these deposits, and the velocity of the streams increasing *pari passu* with the amount of upheaval, their capacity of vertical erosion increased while that of lateral erosion diminished, so that the width of the flood-plain has gradually contracted, leaving a series of benches or terrace levels carved out of the mass of material accumulated in the valley.

In such a case the number and levels of the terraces cor-

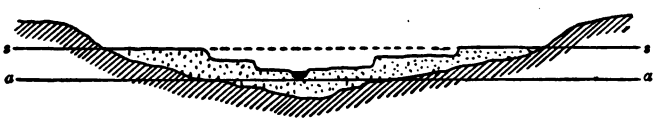

Fig. 34. Terraces cut out of silted up Valley.

respond on each side the stream, but in England there are few instances of such valley-structure, and terraces seldom occur at exactly the same level on opposite sides of a valley, except where an alteration in the course of the stream has caused it to cut through an old terrace, and so to leave a portion on either side of the present channel. Where two opposite terraces appear to correspond, it will generally be found that the bottom of one is really lower than the bottom of the other, and that they have been formed at different epochs in the excavation of the valley.

In some districts the natural drainage of the country has altered so greatly in the course of ages, that long banks and ridges of river gravel are found in situations where no rivers could now flow. Long series of such gravels occur in the neighbourhood of Cambridge.

They commence in a series of patches which occur at intervals along the sides of the long, but now dry, valleys

which run through the chalk hills. The farther they are traced down each valley the larger do the patches become, and the greater is the difference of level between the bottom of the present valley and the height at which the patches of gravel occur, till, at last, they diverge altogether from the existing line of drainage, and stream out to form long-continued gravel-capped ridges which trend more or less in the direction of Cambridge.[1]

Fig. 35 is a section across one of these ridges, near Wilbraham; it owes its existence as a ridge to the river-gravel which rests upon it, and has protected the underlying chalk from destruction; the bottom, therefore, of the ancient valley is here preserved, while the hills and slopes which once formed its sides have long since been destroyed and washed away by the wasting action of rain and springs.

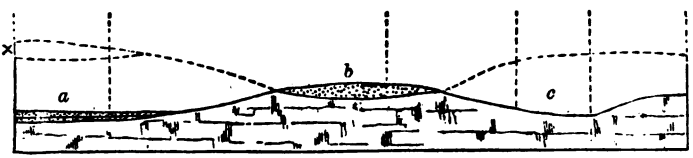

Fig. 35. Gravel Ridge near Wilbraham, Cambridge.
a, newer gravel. *b*, ancient gravel. *c*, chalk.

The dotted lines in the figure indicate the general outline of the ground at the time when the gravels were formed.

Formation of Deltas.—It has been stated that in the lower reaches of a river-course, the stream continues to widen its valley by lateral erosion, now on one side, now on the other, though it no longer exerts any erosive action upon its bottom. On the contrary, it deposits a large quantity of the sand and silt which it brings down, and this is spread out over the surface of the broad alluvial plain in which it flows.

If the river debouch into a lake or into a quiet bay of the sea, where the coast is not swept by any very strong currents, this alluvium expands into a still wider area having a more or less triangular shape, like that of the Greek letter Δ, whence it is called a *Delta*.

[1] See "Post-Tertiary Deposits of Cambridgeshire," p. 46, and "The Geology of Cambridge," Mem. Geol. Survey, p. 82.

The head of the delta is the point where the river originally entered the lake or sea; properly speaking, indeed, the river ends here just as its valley ends, and its waters merely find their way as best they can through the muddy deposit with which it has choked its own mouth. This they do by means of several channels branching off from the main stream, each of which conveys a portion of muddy water to its own mouth, where the sediment is deposited, and the extent of the delta is thus continually increased.

The Rhine when it enters Holland is lost in a great deltoid flat among a number of bifurcating channels, in which its waters are mingled with those of the Meuse, Sambre, and other rivers; these have all contributed to form the low marshy ground of which the Netherlands consist.

The united deltas of the Po and Adige have a length of about 70 miles from Ostiglia to the mouth of the Po, and a seaward breadth of about 50 miles; but they are conterminous with the deltas of the Brenta, Piave, Tagliamento, and Izonzo, so that a continuous tract of marshy land extends for more than 100 miles from the Gulf of Trieste nearly as far as Ravenna. Adria, which was a seaport in the time of Augustus and gave its name to the Adriatic Sea, is now 20 miles inland, and the whole coast-line above indicated has increased by a width of from 2 to 20 miles during the last 2,000 years. All this material has been brought down from the Alps by the tributaries of the above-mentioned streams.

The delta of the Mississippi has an area of 12,300 square miles; it has completely filled up the inlet of the sea which once penetrated deeply into the North American coast, and has projected far into the Gulf of Mexico, carrying out the river by a natural canal 50 or 60 miles beyond the general edge of its delta. The head of this delta taken as the point where the river sends off its first bifurcation (called the Atchafalaya) is about 200 miles distant from the coast. A well has been sunk at New Orleans to a depth of 630 feet without reaching the bottom of the alluvial deposits.

The conterminous delta of the Ganges and Brahmapootra is still larger, for it makes a coast-line of 260 miles in length, and a swampy flat which is 100 miles wide at a distance of

250 miles in the interior, its whole area being probably 50,000 or 60,000 square miles. An Artesian well was bored at Calcutta to a depth of 480 feet, the auger penetrating some old land surfaces at several depths, proving continued depression of the land (*Lyell*). There is probably round the head of the Bay of Bengal enough river deposit to cover all England and Wales to a depth of 200 or 300 feet.

So obviously is the delta of the Nile the production of that river, that Herodotus remarked that "Egypt was the

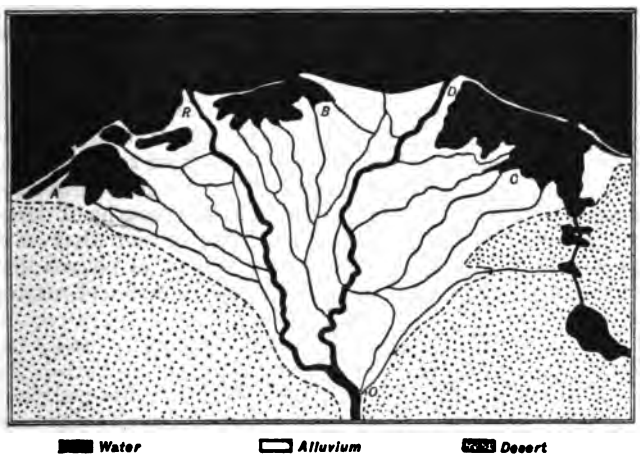

Fig. 36. The Delta of the Nile.

gift of the Nile," and that the sea had probably once flowed up to Memphis, now more than 100 miles from the coast-line, the old gulf having been filled up by the Nile mud, as the Red Sea would be filled up if the Nile were turned into it. The edge of the present delta is about 180 miles wide, but it is now swept by a powerful current, which carries off most of the detritus delivered into it, so that very little addition to the delta has been made in the last 2,000 years. Another result of this current has been to throw sand-banks across the mouths of the lagoons known as Lakes

Mareotis, Bourlos, and Menzaleh, shown in the accompanying plan of the Delta of the Nile, fig. 36; these are, of course, slowly silting-up, and will eventually be dry land.

We need hardly observe that river-valleys do not always terminate in deltas. There are many great rivers which do not block up their own mouths in this way, but pour all their detritus directly into the sea. In some cases the strength and velocity of their currents is sufficient to carry the greater part of the sediment out beyond their mouths; in other cases the estuary into which the river falls is kept open by the scour of the tides. The Amazons and La Plata are instances of rivers with strong and rapid currents which are felt at a distance of more than 100 miles from their mouths; the Thames, Severn, and other rivers of our own islands which empty themselves into estuaries, illustrate the latter case. The large sandbanks, however, which accumulate about the mouths of such rivers, testify to the quantity of material they bring down from the land, and these deposits will be treated of under the head of marine formations. Neither do the deltas at the mouths of large rivers give us the full account of the erosion they have performed, for a large amount of sediment is poured into the sea and distributed over its bed by the action of marine currents.

§ 2. *Deposits formed by Glaciers.*

Moraines.—The moraines of a glacier have already been described (p. 114), and it was stated that on the retreat of a glacier its terminal moraine will remain and form a semicircular mound stretching across the valley.

Such a moraine consists of a confused mass of earth, stones, and boulders heaped together without any regard to size or weight; most of the materials have been shot over the end of the glacier, just as rubbish is thrown down to form a railway embankment. The greater number of the stones, therefore, having been carried on the upper surface of the glacier, will not bear any glacial markings or scratches; those, however, which were fixed in the under surface of the ice, and came in contact with the rocks forming the sides and bottom of the valley, will be polished and scratched on one or more faces.

Old lateral moraines are also found where ancient glaciers have melted away, these moraines remaining as long hummocky ridges or banks along the sides of the valley, and consisting of similar materials to those which compose the terminal moraines.

Examples of such moraines are to be found in many parts of the British Islands, where glaciers formerly existed, viz., in North Wales, in the Lake district, in the highlands of Scotland, and among the hills of Ireland. An excellent example occurs near Killarney, at the northern entrance to the Gap of Dunloe, as described by Mr. Du Noyer.[1]

Three lunette-shaped mounds of local boulder-drift, sand, and gravel are arranged in a rude concentric form, one beyond the other across the mouth of the gap; the two outer mounds are incomplete, their western extremities having been destroyed, but the portions remaining on the east side of the stream measure fully one mile in length by about 100 yards in width, and their south-east ends rest on the flank of Purple mountain at an elevation of about 400 feet. The inner mound is much more perfect, and is cut through in its central part by the river Loe; on the east side of the river it measures 650 yards in length by 150 in width, and on the west side it curves round to the S.W. for a distance of 700 yards. At the north end of the Black Lake is still another deposit left by the retreating glacier, as the climate became warmer.

Till and Boulder Clay.—Ordinary glaciers do not appear to leave any deposits behind them besides the moraines above described. The glaciers of Switzerland have sometimes retreated for considerable distances, leaving the ground they formerly covered exposed to view; consequently, if any deposits were formed underneath the ice, we should expect it to remain on this ground.

It does not appear, however, that such deposits ever occur. Professor Bonney,[2] who has specially examined retreating glaciers for this purpose, thus writes:—"In no case have I been able to find signs of any deposit resembling till or boulder clay; the detrital matter, which is scattered generally sparsely over the slope left bare by the

[1] Explanation of Sheet 173 of "Geol. Survey of Ireland," p. 23.

[2] "Notes on Glaciers," "Geol. Mag." Dec. 2, vol. iii. p. 197.

retreating glacier, has fallen from its surface, like ordinary terminal moraine," neither could he find any such deposit under the ice of the glacier itself. A similar absence of deposits has been remarked in Norway.[1]

It has been supposed, however, that the case is different in the Arctic and Antarctic regions, where the precipitation of snow is very great, and the glaciers are not confined to the valleys, but form a confluent sheet of ice spreading over the whole country, and that under these conditions a mass of débris must accumulate underneath the ice, and may form a deposit of considerable thickness.

To this accumulation the name of Moraine Profonde or Ground-moraine has been given. It must be partly frozen into the bottom of the ice, but it is supposed that some of it is pushed along by the moving ice-sheet, and that portions are detached and allowed to accumulate in hollows and valleys underneath the ice. Furthermore, it is assumed that the ice-sheet passes over such deposits, and allows them to remain undisturbed, notwithstanding the erosive powers usually attributed to moving ice. Finally, we are required to believe that the great weight of the superincumbent ice will exercise an immense pressure upon the material below, and compact the mud and stones into a tough boulder clay.[2]

This hypothesis has been invented chiefly to account for the formation of the hard and tough kind of boulder clay known in Scotland by the name of Till, but Prof. James Geikie has applied it to explain the origin of most other boulder clays.

It must be observed, however, that while this theory has found much favour among geologists, it is by no means universally accepted, and its probability has been strongly disputed by some. The author reckons himself among the number of these doubters, and notwithstanding the able manner in which the power of land-ice has been advocated, he does not think its supporters have proved their case; certain boulder clays may owe their origin to the action of glaciers, but it is more probable that the boulder clay which has such a wide extension over England is a marine

[1] "Proc. Geol. Soc. Liverp.," 1872-73.

[2] See "Great Ice Age," by J. Geikie, second edition, ch. i.

deposit formed near ice-clad shores, but always under water.

In Coast-ice we have an acknowledged agency, the operation of which has been observed, and which must give rise to deposits of a similar nature (see ch. xi.); again, in the water below and beyond the seaward terminations of large glaciers, extensive deposits of mud and stones must be produced; whereas the ice-sheet theory involves many assumptions the truth of which has not been confirmed by any actual observations.

The following are difficulties in the way of accepting this latter theory.

1. No one has yet seen any traces of a ground-moraine under a retreating glacier or an ice-sheet.

2. If it exists, it is probably frozen into the bottom of the ice, and cannot be detached from the moving mass so as to remain in hollows while the ice moves over it.

3. Boulder clay is not only found in valleys, and plains, but has been spread over high ground and low ground alike in a thick and continuous sheet.

4. Boulder clay frequently contains fragments of rock, the parent sites of which are several hundred feet below their present resting-place. They must, therefore, have been carried up by the agent which formed the clay, but it has not been proved that an ice-sheet can move up a slope for any considerable distance.

5. The inconsistency of believing in a great underlying sheet of ground-moraine, and at the same time crediting glaciers with the power of excavating lake basins. Neither one nor the other theory has yet been proved.

6. Actual observation has only shown that where glaciers descend a slope they rest on bare rock and push all loose materials before them; where they reach more level ground they pass over any accumulation of débris without much disturbing it.[1]

§ 3.—*Deposits formed in Lakes.*

Mechanical Deposits.—Where rivers enter lakes, deltas similar to those just described will be formed, but

[1] See Bonney, op. cit. p. 198.

will generally consist of more varied materials; because rivers flowing into lakes usually run with greater velocity than when they enter the sea, and are more liable to floods which sweep down a quantity of coarse débris; thus boulders, gravel, and sand, are either continually or occasionally poured into lakes, besides the finer sediment which rivers everywhere carry.

The detritus thus brought down from the surrounding land is arranged in a definite and peculiar manner, as may be seen by watching any small stream which enters a pool. The particles of sand and gravel swept along by the stream are dropped when they enter the pool or lake, and are spread out in a fan-shaped deposit, the surface of which is nearly level or gently inclined, and ends in a steeper slope, see fig. 37. The inclination of this slope varies with the coarseness of the materials, but is frequently about 30°. Further supplies of débris are pushed along the level sur-

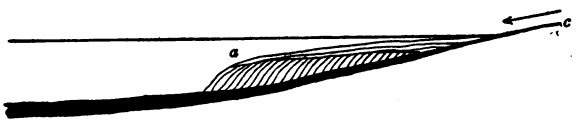

Fig. 37.

face and shot over the edge of the bank so as to form an additional sloping layer, and so the process goes on, successive layers being deposited sometimes of gravel, sometimes of sand, but all sloping in the same direction, viz., away from the mouth of the stream, *c*.

All this time, however, the river is also pouring into the lake a quantity of finer sediment which is carried out far beyond the edge of the delta. The turbid waters of the river, having a greater specific gravity than the clearer waters of the lake, sink beneath the latter and often steal along the bottom for a considerable distance before they part with their burden of suspended sediment. As De la Beche remarks, "if a long trough be filled with clean water, and turbid water be very quietly poured into it at one end, the mode in which the latter finds its way beneath the former will be at once seen."

The fine mud, therefore, which is carried onward by the

current of the river, will be evenly spread over the bottom of the lake in advance of the growing delta, and the delta deposits will be superimposed upon it, as shown in fig. 37.

Besides a large river there may be other smaller streams and torrents flowing into the lake, and each of these will form a small delta and contribute its share of detritus, so that in course of time the lake may be completely filled up by the growth of the deposits above described. The river Rhone is thus gradually filling up the Lake of Geneva, and has already formed a flat alluvial plain sixteen miles long at its upper end. An ancient town called Port Vallais (Portus Valesiæ) stood on the water's edge about 900 years ago, but now it is a mile and a half inland, so much new ground having been formed in the interval. It would be quite possible to calculate the time required for the river to convert the whole lake into a similar plain, through which it would then meander to its present outlet at Geneva.

Sir Charles Lyell tells us that many such filled-up lakes may be found in the course of the Rhone and its tributaries. "If we ascend, for example, the valley through which the Dranse flows, we find that it consists of a succession of basins, one above the other, in each of which there is a wide expanse of flat alluvial lands, separated from the next basin by a rocky gorge, once perhaps the barrier of a lake."[1] In our own country a good instance of such an obliterated lake occurs at Rossthwaite above Borrowdale.

In the case of lakes which are not traversed by any large river, the deposits are rather different. Lake Superior is the largest expanse of fresh water in the world, and numerous rivers run into it, but none form any considerable delta; round its shores there are beaches of sand and shingle, and its bottom consists generally of a very adhesive clay containing shells of the species now living in the lake. "When exposed to the air, this clay immediately becomes so indurated as to require a smart blow of the hammer to break it. It effervesces slightly with diluted nitric acid, and is of different colours in different parts of

[1] Lyell's "Principles of Geology," vol. i. p. 419.

the lake; in one district blue, in another red, and in a third white, hardening into a substance resembling pipe-clay."[1]

Chemical Deposits.—Sediments of the kinds above mentioned are not the only deposits which occur on lake-bottoms. It must be remembered that the sediment in mechanical suspension does not represent the whole of the material transported by a river, for all streams carry more or less mineral matter in solution, and this must also be poured into the lake.

Whether the lacustrine waters retain it in solution, depends upon the amount of evaporation to which they are subjected. The air is always absorbing vapour from broad surfaces of water, and it is usually, if not always, the case, that much more water flows into a lake than ever flows out again. Some lakes have no outlet, even though they are fed by large streams, and sometimes the evaporation is greater than the supply, so that the waters are gradually shrinking in volume. In such cases it is evident that the proportion of matter in solution will rapidly increase, since only pure water is taken out; and when the solution becomes a saturated one, precipitation will commence, and chemically formed deposits will be formed.

Salts in Solution.—The principal salts found in river waters are the following:—

Carbonates of lime, magnesia, and soda.
Sulphates of lime, magnesia, potash, and soda.
Chlorides of calcium, magnesium, and sodium.
Silicates of potash and soda.
Peroxides of iron and manganese.
Silica and alumina in small quantities.

Bischof gives a table of forty-eight different analyses of the river-waters of Western Europe, which show an average of about 21 parts of mineral matter in 100,000 of water. A similar collection of analyses by Roth shows a mean of 19·983 in 100,000 of water.

The amount of matter carried in solution by the Thames has been variously estimated; according to Professor Prest-

[1] Lyell, op. cit. vol. ii. p. 422.

wich there are 19 grains of salts in every gallon of water that flows past Kingston, and the mean daily discharge of water is 1,250 millions of gallons; hence the dissolved matter amounts to 1,502 tons every twenty-four hours, or 548,230 tons in the year. The amount carried by the Upper Elbe out of the Bohemian Basin is about the same (see p. 161).

Mr. Mellard Reade has calculated that the mean amount of solids dissolved in the rivers of England and Wales is 12·23 parts in the 100,000; and that the total annual amount carried by the rivers into the surrounding seas is 8,370,630 tons, which represents a removal of 143·5 tons of material from every square mile of surface per annum.[1]

Carbonate of lime generally forms more than half the total amount of matter in solution; its mean quantity, according to Bischof, being 11·34 in the 100,000. In the Thames, according to Prestwich, about two-thirds of the whole, or 12 grains in every gallon, are carbonate of lime, representing a total amount of 140 tons removed annually from every square mile of the Thames basin above Kingston. The waters of the Rhone appear to remove a larger amount of carbonate of lime from each square mile of drainage basin than any other European river. The total solids in solution amount, according to Mellard Reade, to 232 tons per square mile per annum, and, according to Bischof's analysis, about two-thirds of this must be carbonate of lime.

After the carbonate the sulphate of lime is the next most abundant mineral in solution, and in some rivers forms nearly half the dissolved matter. The quantity in the Thames water at Kingston is about one-sixth the total solids in solution, according to Professor Prestwich.

Less in amount are chloride of sodium, carbonate of magnesia, and silica. The proportion of silica found in river water is believed to depend upon the concomitant amount of organic acids derived from the humus or vegetable soil occurring in the basin of drainage.[2] In the water of the Thames at London Bridge, the amount of

[1] "Address to Liverpool Geol. Soc. 1877," and tabulated statement in "Chemical Denudation."

[2] See Sterry Hunt, "Chemical and Geological Essays," pp. 126, 150.

silica is stated as ·1239 grains in a gallon,[1] or ·214 parts in 100,000; in the Rhine at Strasburg as much as 4·88 parts have been found.

Deposition of Salts.—When river water is discharged into a lake and evaporated, the salts in solution are not all deposited at once. Much of the carbonate of lime is used up by plants and animals living in the lake; but the remainder may be deposited, and when the solution becomes sufficiently saturated, first the carbonates and sulphates and finally the chlorides will crystallize out.

The basin of the Great Salt Lake in Utah, U.S., affords an excellent instance of the gradual desiccation of a large body of water. The present lake is about 80 miles long with an average breadth of 30 miles, but Mr. Clarence King calculates that it had originally a length of about 300 miles, and an extreme width of 180 miles.[2] The old lake was probably at first filled with fresh water, but climatal changes diminishing the supply, evaporation prevailed and the area of the lake grew less and less; the salts were gradually concentrated and finally precipitated over part of the area.

It would appear that the first salt to be separated was carbonate of lime, for calcareous sands and large deposits of tufa are found on the uppermost terraces; while an analysis of the present water discloses the fact that none remains in solution, though large quantities are annually brought in by the rivers. The reason of this seems to be that the carbonate of lime is unable to remain in solution in the presence of alkaline salts, such as the chlorides and sulphates of soda and potash. It is, therefore, quickly precipitated. These alkaline salts are supplied by the numerous mineral springs in the vicinity.

The next salts deposited from the diminishing lake were probably some of the sulphates, and finally, when parts of its area were separated and further concentrated, deposits of sodium chloride were formed.

On the desert plains round the lake, desiccation products are found, which consist principally of chloride of sodium (86 per cent.) with sulphate of lime (9 per cent.), and

[1] Ashley, in "Quart. Journ. Chem. Soc." vol. ii. p. 74.
[2] "Exploration of the 40th Parallel," vol. i. p. 492.

small quantities of the sulphates of soda and magnesia. In Nevada there is a salt-field formed by the evaporation of a lake which at the period of its greatest saturation occupied a basin about 20 miles in length. It is now a solid field of white salt, covered with a thin layer of brine in the winter months which completely evaporates in the autumn. In the middle the deposit of solid salt is five feet thick, but towards the west shore this is overlaid by a fine saline mud, in which beautiful octohedral crystals of salt occur. The solid mass consists chiefly of sodium chloride (97 per cent.) with small quantities of carbonate and sulphate of soda.

The Dead Sea and the Caspian Sea are likewise examples of the concentration of large lakes. The waters of the latter sea are salt, and its volume is constantly diminishing notwithstanding the quantity of fresh water poured into it by the Volga and other rivers. Salt lagoons are formed round its shores, and the surrounding deserts are covered with a salt efflorescence. The salts in solution are the chlorides of sodium and magnesium, the sulphates of lime, soda, and magnesia, with small quantities of the carbonates of lime and magnesia. Before, however, the chloride of soda (rock salt) can be deposited, it is necessary that more than nine-tenths of the bulk of water should be removed by evaporation, and until this saturation point is reached only small quantities of other salts will be deposited. When, however, the concentration has proceeded so far a large deposit of rock salt will take place. Thus in the salt lakes about the mouth of the Volga a compound of the sulphates of magnesia and soda, called Astrakanite, is formed in the winter when the evaporation is not great, while in summer, rapid evaporation causes the deposition of rock-salt.

Lakes Fed by Mineral Springs.—We have hitherto only considered the chemical deposits produced by the evaporation and concentration of ordinary river waters when poured into lakes. But extensive deposits may be rapidly formed in lakes without great evaporation, if their waters are supplied by springs which contain a large amount of mineral matter in solution.

Such mineral springs are especially abundant in districts

where volcanic action has been rife; they are often thermal, and generally impregnated with carbonic acid, so that they usually hold in solution large quantities of carbonate of lime. The carbonic acid escapes as a gas, and the calcareous matter is precipitated upon the lake-bottoms in the form of travertin.

In Sir C. Lyell's "Principles of Geology," a description is given of the lake of the Solfatara, between Rome and Tivoli.[1] This is fed by a stream of warm water proceeding from a smaller lake above; and the water is so saturated with carbonic acid, that the escape of the gas gives it the appearance of being in a state of ebullition. Tufa and travertin are formed in the lake at a very rapid rate. The principal buildings of ancient and modern Rome are built of travertin obtained from the quarries of Ponte Lucano in the same district, where there has evidently been a lake at some remote period in which this deposit has been formed.

Travertin derives its other name of Tibur-stone from the town of Tivoli (ancient Tibur), which stands on an enormous mass of this rock. The walls of the chasm below the cascade of the river Anio disclose a magnificent section of tufa and travertin in horizontal beds for a depth of 400 or 500 feet. Lyell observes: "There can be little doubt that the whole of this deposit was formed in an extensive lake which existed at the close of the period of volcanic activity, by which the lavas and tuffs of the Roman territory were formed. The external configuration of the country has since been greatly changed, and the Anio now throws itself into a ravine excavated in the ancient travertin. Its waters give rise to masses of calcareous stone, scarcely, if at all, distinguishable from the older rock."

Deposits formed by Organic Agency.—In many lakes the carbonate of lime is separated by the agency of plants and animals. Among plants the fresh-water weed called *Chara* consists largely of calcareous matter, and only grows in water containing much carbonate of lime. The small crustaceans termed *Cyprides*, secrete a thin valvular shell, and occur in large numbers in many ponds and

[1] Vol. i. p. 404.

lakes. Lastly, the dead shells of fresh-water molluscs often accumulate in such quantity as to form beds of shell-marl.

Such deposits have been exposed to view by the drainage of small lakes and meres, the marl being useful for agricultural purposes. Sir Charles Lyell states that the marl in the Scotch lakes is almost entirely composed of the shells of mollusca, chiefly *Limnæa, Planorbis, Valvata,* and *Cyclas,* some of them being in a decomposed and pulverulent state, and some retaining their original form.[1] *Cyprides* and the remains of *Chara* are also intermixed, and the whole is compressed into a marl which splits up into thin layers.

Lyell observes that the inflowing waters must bring a constant and copious supply of calcareous matter, otherwise no tufa or shell marl is formed. All the Forfarshire marls occur in lakes which are supplied by springs containing carbonic acid and carbonate of lime; but round Loch Fithie there are no springs, and in it there is no marl, though it is surrounded by such deposits, and in every other respect the site is favourable to the accumulation of shell-bearing animals. The *Charæ,* too, are most calcareous in waters free from mud and strongly impregnated with lime.

Large deposits of marl are found in the old meres of the Cambridgeshire Fens, and Mr. S. B. J. Skertchly attributes their formation principally to the decay of *Charæ,* which still abound in the neighbouring dykes.[2] Shells form, however, a considerable portion of the mass, and there are occasional lines of peaty matter. An analysis of the marl in Whittlesey mere showed that, after subtracting the moisture and organic matter (chiefly due to peat), 87 per cent. of the residue was pure carbonate of lime, 7 per cent. was an admixture of sandy matter, and the remaining 6 per cent. consisted of sulphate of lime, oxides of iron and alumina, and carbonate of magnesia in very small quantities.

A small lake in New Jersey, called Milk Pond, is described as being entirely surrounded by a thick deposit of shell-marl, which seems to cover the whole basin of the lake.

[1] "Principles of Geology," vol. ii. p. 565.

[2] "Geology of the Fenland," Geol. Surv. p. 60.

It is perfectly white, and is mainly composed of bleached shells, and its thickness is known to be more than twelve feet.

Carbonate of lime seems to be chemically deposited in some Irish lakes, in the form of a white, mealy substance, which is thus described by Mr. Jukes.[1] "The beds of the lakes in the limestone district of Ireland have often a thick deposit of white mud, which, when dry, is almost like flour in appearance, and is wholly soluble in acids. It is full of undecomposed fresh-water shells of ordinary living species, but does not itself disclose any trace of an organic origin. My friend, Dr. J. Barker, of Dublin, subjected some of it, at my request, to a careful microscopical examination, but could discover no trace of organic structure. Around lakes that have been partially drained, large deposits of this substance, several feet in thickness, may be seen; and, in sounding some of the lakes, I usually found the lead sank into and came up partially coated with this substance. On some parts of the shores of the lakes there are accumulations of small nodular concretionary-looking balls of about half-an-inch in diameter, which Dr. Allman, of Edinburgh, told me were a species of Nullipore."

2. *Siliceous.*—Deposits, consisting largely of silica, are formed in some lakes by the agency of minute vegetable organisms called Diatoms, which are able to secrete and appropriate the silica dissolved in the water, just as the molluscs secrete the carbonate of lime to form their shells. Diatoms consist of simple cells, either single, or united in a linear series, and each is enclosed in a siliceous case or shell; these cases are often elegant in shape and delicately sculptured on the surface. They are only visible under the microscope, but compensate for their minuteness by their extraordinary abundance, being so prolific that the number of individuals derived from a single diatom in one month would form a bed of silica, 25 square miles in extent and $1\frac{1}{4}$ foot thick (Ehrenberg).

Diatoms are found in the sea, as well as in bogs, stagnant pools and lakes, and thick deposits are sometimes formed by the accumulation of their siliceous cases, or

[1] "Manual of Geology," third edition, p. 384.

frustules. Such is the berg-mehl (or mountain-meal) on the shores of certain lakes in Sweden. This is of such a fine, floury consistency that the inhabitants use it to mix with flour. Diatom earth is also used to make dynamite by mixing it with nitro-glycerine.

In some Nova Scotian lakes, according to Dr. Dawson,[1] the layers of Diatom earth are several feet thick; he describes it as "a white and, when dry, very light, friable, earth, having a floury texture, and showing, when examined in a bright light, an infinity of minute, shining specks." The white clay of Lake Superior may perhaps be of a similar nature (see p. 173).

Fig. 38. Diatoms and Spicules of Spongillæ from the banks of the river Bann.

A bed of similar Diatom earth occurs near the base of the Mourne Mountains, county Down, Ireland. It is described by Dr. Drummond as forming a very light, white substance, resembling in appearance carbonate of magnesia. On the banks of the river Bann, in the same county, there is an extensive stratum of similar earth (see fig. 38). The siliceous frustules belong to species of *Navicula, Gallionella, Coscinodiscus, Gomphonema, Bacillaria,* &c., together with the spicules of fresh-water sponges (*Spongillæ*).

At Bilin, in Bohemia, there is an ancient deposit of siliceous material, 14 feet thick, which is entirely composed

[1] Dawson's "Acadia," p. 14.

of diatoms, and chiefly of a species called *Gallionella distans*. Ehrenberg calculated that a cubic inch of the earth contained about forty-one thousand millions of organisms. It is known locally as *polierschiefer*, being used by lapidaries for polishing purposes. Similar stone found in Italy and elsewhere is called *Tripoli*.

An enormous deposit of infusorial silica, 250 feet thick, has been discovered in the Kawsoh Mountains, Nevada, U.S. Mr. Clarence King [1] describes the rock as soft and earthy in texture, pure white in colour, and so light as to float on water. Some of the single beds are 8 to 10 feet thick, and about 90 per cent. of the mass is pure silica. The diatoms are referable to 46 different species, of which the most abundant are *Gallionella granulata*, *G. sculpta* and *Spongolithis acicularis*.

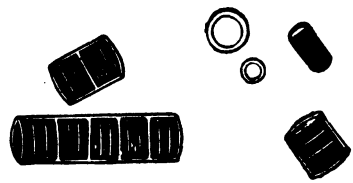

Fig. 39. Gallionellæ (highly magnified).

3. *Ferruginous*. The substance known as Bog-iron-ore was also shown by Ehrenberg to be the product of a particular Diatom called *Gallionella ferruginea*, which forms long threads or filaments consisting of a series of minute cells. Professor Bailey thus describes their appearance in the pools near West Point, United States:—"The bottoms of these are literally covered in the first warm days of spring with a ferruginous-coloured mucous matter about a quarter of an inch thick, which, on examination by the microscope, proves to be filled with millions of these exquisitely beautiful siliceous bodies. Every submerged stone, twig, and spear of grass is enveloped by them; and the waving plume-like appearance of a filamentous body, covered in this manner, is often extremely elegant." The

[1] "Exploration of the 40th Parallel," vol. ii.

iron ore formed in such pools and bogs consists chiefly of silica and peroxide of iron; it occurs in layers under some Scotch bogs, where it is generally called "*the pan*," and the Diatoms composing this pan probably lived in the lake which afterwards became a peat-growing bog.

CHAPTER XI.

MARINE DEPOSITS.

§ 1. *Mechanically formed.*

IN describing the operations of a river, we have followed the course of the detritus transported by its current, and have seen, that though this is temporarily deposited at certain points along the river-valley, yet most of it is eventually moved on again and triturated into smaller and smaller particles. Sediment is thus continually brought down from higher to lower levels, and never finds a permanent resting-place until it is carried into a lake or into the sea. Even delta-mud is liable to removal, and from its mouth the river is constantly discharging a cloud of sediment, which is carried away by the tidal currents and spread over the sea-bottom.

We must also remember that besides this visible sediment there is much invisible material dissolved in the water, and that this latter also is poured into the sea.

Excepting, therefore, the small portion which is intercepted by lakes, the sea is the ultimate recipient of all materials eroded from the land. We shall first consider what becomes of the matter in mechanical suspension, and, secondly, account for the disposal of that in chemical solution.

Assortment of Material.—Let us commence with the case of a rocky coast where small rivers with rapid currents bring down detritus of all kinds and sizes from large stones to fine mud. The order in which these materials are deposited must especially be noticed; as the river-current enters the sea it will first deposit the pebbles, next the smaller stones and coarse sand, farther out fine sand, and last of all, silt and mud. This order of succession is always maintained except where interrupted by local currents and influences. The width and extent of these deposits will,

however, vary from time to time; when a river is in flood the coarser materials will be carried out to a greater distance, so that pebbles and shingle will be deposited over a tract of sand, and sand will invade the region of mud: again, when the river is low, clay or mud will settle down nearer shore, as it did before the flood-time, and cover up the outer beds of sand. In this way wedge-shaped or lenticular deposits of the various materials will be formed and interbedded with each other, as indicated diagrammatically in fig. 40; *a* representing shingle; *b*, beds of sand, and *c* beds of mud or clay.

There will be a further assortment of material according to the differences in the shape and specific gravity of the particles composing the muddy sediment. This subject has been investigated by Mr. Babbage, who supposes the case of a river, the mouth of which is 100 feet deep (and a

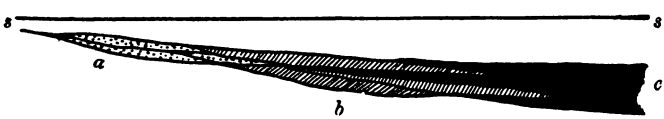

Fig. 40. Lenticular deposits on a sea-bottom.
s, *s*, = the surface of the sea.

current of 2 miles per hour), delivering four varieties of fine detritus into a sea which has a uniform depth of 1,000 feet over a great extent, which sea is traversed by an ocean current moving in the same direction and with the same velocity.

He takes for granted that the four varieties of sediment are such as, from their size, shape, and specific gravity, would fall through still water, the first 10 feet per hour, the second 8 feet, the third 5 feet, and the fourth 4 feet. The combined effect of the downward motion of the detritus and the onward motion of the water, would then bring the first variety to the bottom of the sea, at a distance of 180 miles from the river's mouth, and strew it over a space 20 miles long; the second variety would only begin to reach the bottom 225 miles from the river's mouth, and would be spread over 25 miles, and so on, as in the following table:—

No.	Velocity of fall per hour.	Nearest distance of deposit to river mouth.	Length of Deposit.	Greatest distance of deposit from river mouth.
	Feet.	Miles.	Miles.	Miles.
1	10	180	20	200
2	8	225	25	250
3	5	360	40	400
4	4	450	50	500

We should thus have, proceeding from the same river, and poured into the sea either simultaneously or at different times, four different and widely separated patches of mud or clay on the sea-bottom.

It is, of course, not only from the detritus brought down by rivers, that deposits of sand and mud are formed; large contributions are supplied from the results of coast erosion, and similar deposits are produced even off coasts where no large rivers enter the sea and where the material must therefore be obtained chiefly from the action of the surf upon the coast-line. Thus for *several thousand miles* along the western coast of South America, comprising the larger parts of Peru and Chili, there is a perpetual rolling of shingle along the shore, parts of which are incessantly reduced to the finest mud by the waves and swept out into deep water by the tides and currents. Here, therefore, the successive deposits of shingle, sand, and mud, will be much more regularly disposed than at the mouths of rivers; the coarser portions always nearest to the shore, and the finer sediment furthest away from it.

The same is the case along the eastern coast of Patagonia, and the soundings taken between Santa Cruz and the Falkland Islands in H.M.S. "Beagle," are mentioned by Mr. Darwin[1] as a good instance of this assortment of material, the size of the stones decreasing regularly with the distance from shore:—

[1] "Voyage of the 'Beagle,' 1876."

Miles from Shore.	Depth in Fathoms.	Size of Material.
2 to 4	11 to 12	Pebbles as large as walnuts with others of smaller size intermixed.
4 to 7	17 to 19	Pebbles about the size of hazel nuts.
10 to 11	23 to 25	Pebbles about the size of peas.
12	30 to 40	Pebbles $\frac{2}{10}$ of an inch diameter.
22 to 150	45 to 65	Coarse to fine sand.

Littoral or Shore Deposits.—It must not be supposed, however, that all the detritus poured into the sea by rivers, or obtained by coast-erosion, is distributed in this regular manner. The sea-shore is not always bordered by a shingle beach, neither is the finer sediment invariably carried out to a distance from land. Many rivers never carry anything coarser than sand or silt into the sea, even when floods have occurred in the higher parts of their valleys. Other rivers terminate in estuaries, where they only deposit the finest mud. Again, the materials derived from the erosion of cliffs are often carried laterally along the shore to great distances; the set of the currents varies with the height of the tide, and sometimes an undercurrent will set in one direction, while there is an overflow in a different direction, so that much even of the finer sediment may be carried along the shore and deposited where the currents slacken in bays or inlets.

Thus there are tracts along every coast-line where the land is gaining upon the sea in consequence of the restoration of some of the material which has been torn from it elsewhere. Shingle-beaches, river-bars, and sand-banks are being formed along shores which do not supply the material of which these deposits are composed, sheltered bays and estuaries are being silted up with materials introduced by marine currents, and the overplus of sand thrown up by the waves is blown by the wind into sand hills (see p. 145) which often serve to protect the newly formed and low lying land from the effects of storms and high tides.

Shingle Beaches.—We have seen that the coarser portions of the débris won from the land are generally left or washed up on the shore near high-water mark, and form the

shingles or pebble-beaches of which mention has already been made.

Attention to the changes of a shingle-beach will soon show that besides the moving of the stones backwards and forwards with every tide there is also a general lateral movement along the shore. This is due to the set or inclination given to the waves by the prevalent winds and currents; the breakers thus come to have a slightly oblique action; they do not drop a pebble exactly where they picked it up, but are constantly shifting the pebbles a little further on in one direction. The beach, therefore, considered as a whole, may be said to travel in that direction, until it is arrested by some point of land, or by some artificially constructed barrier.

On the east coast of England sand and shingle travel from north to south, because a strong current sweeps southward along the shore. On the south coast, beaches travel eastward in consequence of the prevalent winds and strongest currents both setting from the S.W. If a pier or groin be erected any where on this coast a bank of shingle will be gradually accumulated on its western side. Long shingle beaches are formed at certain points and nearly all the pebbles composing them have been obtained from the cliffs and shores to the westward of that place.

The Chesil Bank, on the coast of Dorset, is a good instance of such a beach. It commences near Burton Bradstock, and extends as far as the Isle of Portland, a distance of 17 miles. For the first 5 miles it is banked against the shore; from Abbotsbury onwards there is a narrow channel or estuary, called the Fleet, on its inner side, this section of its length having a height of 20 to 30 feet above high-water mark, and a breadth of about 500 feet. The last 5 miles form a bar or isthmus connecting the Isle of Portland with the mainland, and at the S.E. end of this, its height is 40 feet and its breadth about 600 feet. It is a remarkable fact, that although the pebbles composing the beach have all come from the westward, those at the N.W. end are very small, and they gradually increase in size towards the S.E. The reason of this is probably to be found in the greater size of the waves which break upon the south-eastern end, while nearer the head of

the bay the waters are quieter and more protected from storms. The larger waves throw up the larger stones, and thus the material coming from the west is sorted according to size and weight along the whole length of the Chesil Bank.

Hurst Castle Bank is another good example of a shingle beach. This juts out from the Hampshire coast, across the western entrance of the Solent, thus forming a bar which is about two miles long, 70 yards broad, and 12 feet high. It consists of rounded flints derived from the waste of the gravel-capped cliffs to the westward.[1] Other beaches formed in the same way of material coming from the west occur at Eastbourne and Dungeness.

Silting-up of Bays and Estuaries.—In open bays with low coasts and gently-sloping shores, deposits are always taking place, now in one part, now in another, as the banks of sand and silt change with the shifting currents. Part of the materials is brought down from the surrounding land by the streams which enter the bay, and part is brought into the bay by the tidal currents, and has been obtained from the erosion of other coasts.

It often happens that large tracts along the margin of bays and estuaries are gradually silted up and converted into dry land. This is notably the case with two of the largest bays on the English coast, viz., Morecambe Bay and the Wash. Large tracts have been raised above the level of ordinary high tides at the head of both these bays, some portions of these having been reclaimed and brought under cultivation, while other portions are still awaiting embankment and utilization.

The process of silting up can be watched in operation along the shores of the Wash and north-east Lincolnshire. The strong current from the north brings sand and silt into the bay of the Wash, and the waters of every tide bear along a certain amount both of the coarser and finer material. The former is naturally deposited before the latter, and forms sand-banks and sandy flats which extend up to the limits of ordinary high-water mark, but are constantly varying in their position and conformation. Inside these

[1] Lyell's "Principles of Geology," vol. i. p. 531.

sand flats, are mud or silt flats which are only covered at spring tides. When the water reaches these higher flats, the force of the tide is slackening, and the current is never strong: the muddy waters slowly spread over the nearly level surface, and much of the sediment which they carry is deposited during the slack of the tide. This deposit remains where it rests, for the slight movement of the ebb is not sufficient to disturb it, although it is capable of carrying away such sediment as remains in suspension.

The tract of shore, therefore, which lies between the high-water marks of ordinary tides and spring-tides, is slowly raised by the thin sheet of mud which is spread over it at every spring-tide; every such sheet or layer forms a separate lamina, and the whole accumulation is a deposit of laminated silt.

When the surface of the flat has thus been raised to a certain height, the glass-wort (*Salicorina herbacea*), locally known as the samphire, begins to grow upon it, and facilitates the further deposition of silt, which now rapidly accumulates. The surface becomes gradually covered with sea-thrift and other marsh-plants, and passes into the condition of "green marsh," which is only overflowed at very high spring-tides. Mr. Skertchly observes that the "samphire marsh" is always distinguished from that which, having become covered with verdure, is called "green marsh;" also that the two tracts occupy different levels, the samphire marsh being only 8·6 feet above Ordnance datum, and the green marsh averaging 11 feet above the same datum.

Gain of Land on the East and South Coasts.—As we have already indicated those parts of our eastern and southern shores which are suffering from the destructive action of the waves, we may now mention those places where the opposite process is taking place, and where the deposition of material is resulting in the accretion of new land.

Yorkshire.—The only part of the Yorkshire coast where new land is being formed to any extent, is along the shore of the Humber from Hull to Spurn Point. Spurn is a low peninsula of gravel and sand, which is said to be increasing at the rate of 6 yards a year, all the material being ob-

tained from the waste of the Holderness coast. Inside this protecting promontory are a series of marshes formed by the accumulation of the mud and silt brought down by the streams which drain into the Humber. In a boring on Sunk Island more than 50 feet of such alluvium was pierced.

Lincolnshire.—The whole coast of Lincolnshire from the mouth of the Humber to the Wash consists of newly-formed land, and is known by the name of the Marsh, although the whole of it is now drained, and the greater part under cultivation. The length of this tract from Cleethorpes Cliff to Gibraltar Point, near Wainfleet, is about 35 miles, and its average width from 3 to 4 miles; the soil consists of a brown silty clay, and it is bordered by a line of sand-hills which protect it from the inroads of the sea. Beds of peat containing branches and trunks of trees are interbedded with the marine silts and clays, and mark periods when deposition was interrupted; but the series is essentially marine, and is from 30 to 40 feet thick near the coast. The sediment of which it is composed has been derived partly from the erosion of the coast of Holderness, and partly from the supply brought down by the Humber. The marine current setting southward, and the river current flowing eastward partially check and counterbalance one another, and this check has resulted in the deposition of much of the sediment brought down by both currents. Although of recent formation, the marsh-land has rather diminished than increased during historic times, and has often suffered from incursions of the sea, when the waves have succeeded in breaching the sand-hills. The Lincolnshire Marsh-land passes southwards into the wide level of the Fen-land, which is not exactly a delta (as sometimes stated), but a silted-up bay or estuary. The silts and clays of the Fens are not fluviatile, but marine deposits; they are a continuation of the marsh beds, and have been formed in the same way. Mr. S. B. J. Skertchly has shown that the material is brought in from the sea, and is deposited at the slack of high tide. He states [1] that in some places a breadth of 3 miles of land has been formed since the Roman occupation, and that the process is now going on. About 55 square miles were

[1] "Geology of the Fenland," Geol. Surv. Mem. pp. 9, 182.

thus added to England between the second and seventeenth centuries, *i.e.* in 1,500 years; assuming, therefore, that the rest of the Fenland has been accumulated at the same rate, and estimating the area of silt and clay land at 550 square miles, the time occupied in its formation will have been 15,000 years.

Norfolk.—Accretion has been taking place for many years along the north coast of Norfolk; low sand-hills or dunes are thrown up along the shore, and the harbours of Clay and Wells have been partially silted up. On the east coast the estuaries were formerly much more open than they are now. Between Eccles and Winterton hills of blown sand have barred up and excluded the tide from many small estuaries. At Winterton there is an inland cliff about a mile long and some distance from the sea. Again, from Happisburgh, southwards, hills of blown sand extend as far as Yarmouth, where they spread out into extensive dunes.

"In the time of the Saxons the valley of the Yare was a great estuary, and extended as far as Norwich, which city is represented even in the thirteenth and fourteenth centuries as 'situated on the banks of an arm of the sea.' The sands whereon Yarmouth is built, first became firm and navigable ground about the year 1008, from which time a line of dunes has gradually increased in height and breadth, stretching across the whole entrance of the ancient estuary, and obstructing the ingress of the tides so completely, that they are only admitted by the narrow passage which the river keeps open, and which has gradually shifted several miles to the south."

"By the exclusion of the sea, thousands of acres in the interior have become cultivated lands; and, exclusive of smaller pools, upwards of sixty fresh-water lakes have been formed, varying in depth from 15 to 30 feet, and in extent from 1 acre to 1,200. The Yare, and other rivers, frequently communicate with these sheets of water; and thus they are liable to be filled up gradually with lacustrine and fluviatile deposits, and to be converted into land covered with forests."

"In like manner it is evident that at some remote period the river Alde entered the sea at Aldborough, until its

ancient outlet was barred up, and at length transferred to a point no less than ten miles distant to the south-west. In this case ridges of sand and shingle have been thrown up between the river and the sea, and an ancient sea-cliff is now to be seen inland."[1]

The coast of Essex is bordered by a series of marshes which stretch from the estuary of the Blackwater to that of the Thames. South of the Clacton coast, a broad ridge of shingle and sand extends to St. Osyth's Point, and it is inside this that the marshes commence; they skirt the estuaries of the rivers Crouch and Blackwater, and are in some places five miles wide.

In Kent, as elsewhere, the land is losing at some points and gaining at others. "The isle of Thanet was, in the time of the Romans, separated from the rest of Kent by a navigable channel, through which the Roman fleets sailed on their way to and from London. Bede describes this small estuary as being, in the beginning of the eighth century, three furlongs in breadth; and it is supposed that it began to grow shallow about the period of the Norman Conquest. It was so far silted up in the year 1345, that an Act was obtained to build a bridge across it; and it has since become marsh-land, with small streams running through it."

The rich level tract called Romney Marsh, lying between Hythe and Hastings, is the site of a silted-up bay; measured along the coast, its frontage is about 10 miles in length, and across the centre it is 5 miles deep. The sea is now excluded from the marsh, partly by natural barriers of blown sand and shingle, partly by artificial banks, but the greater part of its surface is below the level of high tide, and underneath the clays and peats which form the soil, sand is always found, extending sometimes to a depth of 70 feet. The marsh has received great accession, within historic times. The town of Rye, in the south part of the marsh, was once destroyed by the sea, but is now two miles distant from it. "Mr. Redman has cited numerous old charts and authorities to prove that the average annual increase of the promontory of shingle called Dungeness, amounted for two centuries previous to 1844, to nearly six

[1] Lyell's "Principles of Geology," vol. i. pp. 516, 517.

yards."[1] He observes that "this great accumulation of shingle is composed for a distance of about 2 miles of undulating ridges marking the periodical accessions made to the coast, like the rings of growth in timber."

Sussex.—Between Hastings and Eastbourne there is a considerable area of marsh, which doubtless occupies the site of a silted-up bay. Many changes have taken place in its shore-line of late years, the general result being a loss of ground at the eastern end, and a gain in the western portion between Pevensey Bay and Eastbourne; great banks of shingle have been here thrown up, completely blocking the haven which once existed at the former place. In Pevensey Level the general succession of deposits is—(1) Vegetable soil; (2) Clay, with fresh-water shells; (3) Clay, with marine shells.

The Lewes Levels between Newhaven and Lewes occupy the site of an estuary which had been silted up within the last 800 years. The usual succession of beds found here is described by Dr. Mantell as follows, the total depth being from 30 to 36 feet:—

1. A bed of peat 5 feet thick, enclosing trunks of trees.
2. Blue clay, containing fresh-water shells.
3. Blue clays, containing a mixture of fresh-water and marine shells.
4. Blue clay, with marine shells only, and skull of Narwhal.
5. At bottom a bed of pipeclay derived from subjacent chalk.

The contents of these deposits give the key to the whole history of their formation. The clay with marine shells indicates the period when the sea had free access to the valley; subsequently a shingle bar was formed across its mouth, blocking out the salt-water, and causing the formation of a marsh. The gradual change from salt to fresh-water conditions is plainly shown by the increasing proportion of fresh-water products, till at length it became a land surface, and supported a thick growth of forest.[2]

Between Brighton and Selsey the coast-line has undergone important alterations in recent times. The land

[1] Lyell's "Principles of Geology," vol. i. p. 528.
[2] Mantell's "Wonders of Geology," seventh edition, p. 62.

which has been lost at Selsey, Bognor, and elsewhere by the encroachment of the sea, has been regained by the silting up of the estuaries of the rivers Adur and Arun and other smaller inlets along the coast.[1] These have been converted into level tracts, through which the rivers pursue a meandering course. The materials with which these old estuaries are filled consist of silt, sand, and gravel, and often contain marine shells of existing species.

Selsey, as its name implies, was once an island, and was separated from the mainland by a shallow estuary, the site of which is now occupied by Thorney Marshes and Pagham Harbour. The old historian Bede (A.D. 731), describes the place "as encompassed by the sea on all sides except the west, where is an entrance about the cast of a sling in width; which kind of place is by the Latins called a peninsula." By the time of the Conquest, however (A.D. 1060), it appears to have been completely joined to the mainland: and we may safely infer that the material of which Thorney Marshes are formed was mainly supplied by the wasting of the shore to the westward.

The largest area reclaimed from the sea in the south of England is the wide tract of marsh stretching inland from the head of Bridgewater Bay in the Bristol Channel. The waters of this bay once stretched eastwards to Ilchester and Glastonbury, but have been gradually displaced by the silt and mud brought down by the rivers Axe, Brue, and Yeo. At the commencement of the Christian era this was a wild waste of marsh and bog, like the Fens of Lincolnshire, but the Romans built sea-banks to keep out the tide, and these have been maintained ever since.

Deposition increased by Depression.—It is evident that when any part of a bay, or estuary, is silted up to the level of high-water mark, no farther deposition can take place over its surface: the material brought down by the streams is carried on and deposited outside that already accumulated, and so the newly-formed land increases by the addition of matter to its margins, as already explained in the case of deltas.

It is clear also that if the area of deposition is being

[1] Dixon's "Geology of Sussex," new edition, p. 77.

raised, the silting-up will be accelerated, for the amount of matter deposited over any one spot will be less than if the area were stationary. On the contrary, if the whole area be permanently lowered a few feet, mud and silt will again be thrown down and will continue to accumulate until it raises the surface to the former level, and thus a greater amount of matter will be deposited over a given spot. Continued subsidence will allow of equally continued deposition, and in this manner the thickness of deposits may be indefinitely increased.

Now it has been observed that, where thick deposits are being formed, a certain amount of subsidence is also taking place; some writers, therefore, have suggested that this subsidence is caused, or increased, by the weight of the material, which has been gradually accumulated.

Without discussing this question of cause and effect, it will be sufficient to mention some instances where thick deposits have been formed in a subsiding area. There is no doubt that the plains of the Po were once occupied by an extension of the Adriatic Sea, which has been filled up by the advance of the Delta. The land has continually increased at the expense of the sea during historical times, the width of the new accessions being greatest at the mouths of the Po and Adige, but other smaller rivers have contributed to this increase, so that a continuous strip of new land has been formed along the west coast of the Venetian Gulf, as already described (see page 166).

"But although so many rivers are rapidly converting the Adriatic into land, it appears, by the observations of M. Morlot, that since the time of the Romans, there has been a general subsidence of the coast and bed of this sea in the same region to the amount of 5 feet, so that the advance of the new-made land has not been so fast as it would have been had the level of the coast remained unaltered. The signs of a much greater depression anterior to the historical period have also been brought to light by an artesian well, bored at Venice in 1847, to the depth of more than 400 feet, which still failed to penetrate through the modern fluviatile deposit. The auger passed chiefly through beds of sand and clay, but at four several depths, one of them very near the bottom of the excavation, it

pierced beds of turf, or accumulations of vegetable matter, precisely similar to those now formed superficially on the extreme borders of the Adriatic. Hence we learn that a considerable area of what was once land has sunk down 400 feet in the course of ages." [1]

The borings made in the deltas of the Ganges and the Mississippi disclose similar facts, the well at Calcutta being 481 feet deep, and that at New Orleans 630 feet without reaching the base of the alluvial deposits. That at Calcutta is especially remarkable, because the lower 80 feet of the boring consisted of sand, shingle, and boulders, showing that the velocity of the stream and, therefore, the slope of its watercourse, must have been very much greater at that time, and that subsequent depression of the land has lessened the velocity of the stream, and consequently the rate of erosion. The Ganges cannot now carry gravel farther than a point about 400 miles from the sea.

Deposits in Shallow Seas.—Much of the material gained from the land is carried seaward by the retiring tide and by the currents which set along the shores, and is eventually deposited at a greater or less distance from the land, according to the strength of the current and the fineness of the material.

The seas surrounding our own islands are exceptionally shallow, the German Ocean being in few places more than 50 fathoms deep, and there are only two parts of the Irish Sea which reach that depth. From the deposits which are now being formed in these seas, we may obtain a good idea of the manner in which the materials worn from the surrounding shores are disposed over their bottoms. The Admiralty charts, like all other good charts, indicate by letters the nature of the bottom as well as the depth; and by colouring these charts with different colours, according as the bottom consists of sand or mud, we get a very instructive map of the deposits now being formed.

In the German Ocean mud is only found in the central and deeper parts, between Denmark and the Dogger Bank, and in the mouth of the Baltic between Denmark and Nor-

[1] Lyell, "Principles of Geology," tenth edition, vol. i. p. 423. The successive depths at which turf beds occurred were 95, 155, 275, and 410 feet.

way, all other parts within some miles of the shore having a sandy bottom.

In the English channel there is nothing to be found but sand, often mixed with stones or gravel; but opposite the mouth of the Bristol Channel there is a large, irregular patch of mud, stretching between the Scilly Islands and the coast of Wexford. This is at the bottom of water varying from 40 to 60 fathoms in depth, and it is entirely surrounded by rather shallower water, the bottom of which is marked as sand. Another larger area of mud commences farther west, where the depth increases to 60 or 70 fathoms, and this leads out by a narrow lane of 80 fathoms towards the oozy bottom of the deep Atlantic.

In the Irish Sea, half-way between the coasts of Wexford and Cardigan, there is a considerable area of mud in water of 50 to 60 fathoms' depth, and another small one between Bray Head and Holyhead, in a hollow varying from 60 to 86 fathoms, surrounded by sandy ground of 20 to 30 fathoms only. A long strip of mud commences between the Isle of Man and the coast of Antrim, and extends through the North Channel into the Firth of Clyde; the southern parts of this basin are from 60 to 70 fathoms deep, but the central part south of the Mull of Cantire, is more than 100 fathoms in depth. The shallower slopes on either side have a sandy bottom.

Limits of Mechanical Deposits.—It is evident from Mr. Babbage's calculation, above quoted, that there is a limit to the outward extent of the deposits derived from the erosion of the land. Under the conditions assumed by him this would be at a distance of 500 miles from the shore, but these conditions nowhere exist, and the extension of such deposits is in reality much less.

In the first place, the sea never has a uniform depth of 1,000 feet (166 fathoms) near the land, its bottom invariably presents a gentle average slope for a greater or less distance from the coast, and then plunges with a much steeper incline to the depths of the ocean; so that the great continents are as a rule surrounded by a belt of shallow water which gradually deepens to 100 or 150 fathoms, while outside this the depth rapidly increases to 1,000 fathoms or more. This belt of comparatively shallow water is

seldom more than 100 miles wide, and its bottom is, in fact, the platform upon which the great continents stand (see p. 136). Again, it is assumed that the ocean current which bears the river-borne detritus onward flows in the same direction as the river, viz., directly out to sea; but this can seldom be the case, for most marine currents, whether in seas or oceans, sweep along the coasts or set outwards in an oblique direction from the shore. Sediment, therefore, which is carried by such currents will not reach so great a distance from land as 500 miles, for supposing that the current sets outward from the river's mouth at an angle of 45° with the trend of the shore, sediment carried 500 miles in a linear direction will only be 350 miles from land when deposited. Thirdly, it is probable that such superficial currents do not retain their surface velocity down to any great depth.

As a matter of fact, the examination of the sea-bottom made during the voyage of the "Challenger" showed that mechanically-formed deposits were usually confined to a narrow tract near the coast, not more than from 50 to 100 miles wide, and that the finest mud was only occasionally found at distances of 150 or 200 miles from the land. Beyond these limits the deposits were universally those of a chemical or organic origin, the only mechanical ingredients being fragments of pumice floated by the waves and volcanic dust carried by the winds.

It would appear, therefore, that the greater portion of sedimentary rocks, certainly all the coarser-grained varieties, have been formed within a distance of 100 miles of the land; the chief exceptions being where shallow seas of 100 or 150 fathoms have extended to a greater distance from the coast, as in the case of the German Ocean already mentioned, and where large rivers with strong currents, like the Amazon, have carried out sediment to a greater distance from the land.

Marine Deposits due to the action of Ice.—In considering the manner in which the products of ice-erosion are deposited on the sea-bottom, it must be remembered that there are two distinct kinds of ice in the sea, viz., land-formed ice, and sea-formed ice. The first is delivered into the sea from the end of glaciers, the second is

produced by the freezing of the sea itself along the coast. Both carry detritus, but since the conditions of the two cases differ, it is possible that the deposits resulting from their action differ also in some degree, though perhaps not so greatly as might at first sight appear probable. We shall, however, describe each case separately.

1. *Glaciers and Icebergs.*—In the regions of Arctic cold where the snow-line reaches the sea-level, the glaciers descend into the sea, and large masses of ice are constantly breaking off and floating away as icebergs. These bergs often carry stones and blocks of rock which are dropped on the sea-bottom as the mass of ice gradually melts away.

Greenland, Spitzbergen, and other lands within the Arctic circle are entirely buried under a vast ice-cap, which is slowly and continually moving outwards and seawards in

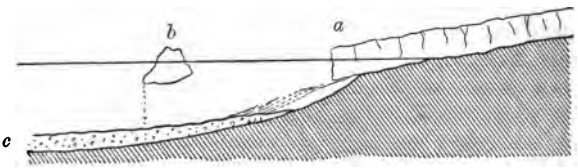

Fig. 41. Termination of a glacier in the sea.

the form of enormous glaciers which descend between the rocky promontories of the coast, and spread out for many miles beyond the real shore. Some of these glaciers are 2,000 feet thick, and terminate in high cliffs more than 200 feet in height, which sometimes continue like a wall for a distance of 50 or 60 miles in front of the land. From these cliffs gigantic icebergs are from time to time dislodged, often rising from 100 to 200 feet out of the sea, which involves a thickness of nine or ten times that amount below water.

Fig. 41 is intended to illustrate the termination of a glacier in the sea, *a* representing the glacier, *b* one of the bergs detached from it, and *c* a deposit of clay and stones on the sea-bottom. We have now to describe the manner in which this deposit is formed.

We have seen that in the case of inland glaciers the rock-

fragments which they bear along fall on to the terminal moraine, while the finer detritus is carried away from the locality altogether by the stream which issues from beneath the glacier. When, however, a glacier terminates in the sea, both these kinds of detritus are deposited together in the bay or fiord where the glacier ends.

Sub-glacial rivers occur beneath the inland ice-sheet of Greenland, just as they do beneath the Alpine glaciers, and along certain parts of the coast where the ice does not reach the sea, these streams burst out as turbid torrents from below the terminal wall of ice. So also do they escape beneath the glaciers which descend into the gulfs and fiords, and where the ice is protruded far into the sea, the muddy water is discharged at a depth considerably below the level of the water, and the fine powdery mud sinks to the bottom in a continuous cloud without being transported far from the spot.

At the same time the bergs broken off from the glacier will drop a large part of their freight of stones and boulders as they float away; much more débris of the same kind will be contributed by the periodical melting of the coast-ice; and all will be embedded in the mud which is thus being deposited on the sea-bottom.

A part of the west coast of Greenland along Davis Strait has been elevated so that a portion of the old sea-bottom is exposed to view. Of this tract Dr. Robert Brown has given an interesting description.[1]

"The hills are low and rounded, and everywhere scattered with perched blocks and boulders. . . . In other localities, in the hollows or along the sea-shore, we see several feet of the glacier-clay full of Arctic shells such as are now living in the sea, while in other places the clay is bare of life. . . . I have found this clay everywhere along the coast, and in Leer Bay, south-west of Claushaven, in knots of this clay are found impressions of the Augmaksaett (*Mallotus arcticus*), a fish still quite abundant in Davis Strait." He describes these clays as being similar to the laminated boulder-clay found in the Clyde valley.

We may note, therefore, that fiords, which have been

[1] "Quart. Journ. Geol. Soc." vol. xxvi. p. 690.

once occupied by such glaciers, and have since been elevated, will present two peculiarities; *first*, their upper ends or heads will be continuous with the valley down which the glacier descended; *secondly*, their lower ends will be filled up with deposits of glacial clay.

2. *Coast-ice.*—The nature and action of coast-ice have been described on p. 131. It was there stated that the ice-foot becomes loaded with a great quantity of rock-débris, much falls on to its surface from the cliffs above, many stones and boulders are picked up from the shore to which it is frozen. When summer comes the ice breaks off from the coast and floats away with its load of land-débris, drifting about in the bays and along the coast, but not often travelling very far out to sea. Sometimes the floes are driven upon the shore during storms, and packed to a height of 50 or 100 feet, sometimes they break up over comparatively deep water, and their freight of mud and stones is then scattered over the sea-bottom.

The deposits thus formed must be accumulated rapidly and continuously, the materials are very various and are dropped indiscriminately upon the sea-bottom, the portions already deposited are constantly disturbed by falling fragments, and frequently exposed to the impact and pressure of ice-floes; under these circumstances they are not likely to present the clear lines of stratification which other sediments slowly accumulated and sorted by current action always present.

Furthermore, this glacial deposit will not be confined to valleys, but will spread over the whole sea-bottom near the coast, and will cover all its irregularities.

It should be noted, too, that some of the boulders transported by coast-ice are carried to lower levels, and others to higher levels, the latter being especially the case if the whole coast is sinking. The ice-floes will then be driven further and further on to the land, bearing with them the stones and blocks derived from those parts of the shore which were previously exposed to their action, so that by this means rock fragments may be carried upward in course of time to levels far above that from which they were originally detached.

Mr. Darwin long ago explained this transportal of

boulders from lower to higher levels on the hypothesis of a gradual submergence of the country while exposed to the action of coast-ice.[1] He remarks that fragments of rock "from being repeatedly caught in the ice and stranded with violence, and from being every summer exposed to common littoral action, will generally be much worn; and from being driven over rocky shoals, probably often scored. From the ice not being thick, they will, if not drifted out to sea, be landed in shallow places, and from the packing of the ice, be sometimes driven high up on the beach, or even left perched on ledges of rock."

During such submergence thick deposits of clay and stones must be formed, and will be subjected in many places to the friction and pressure of grounding bergs or of ice-sheets resting on the bottom. We may readily imagine, therefore, that in these localities compact boulder clays would be formed, while in other places the action of currents would sort the materials and arrange them in stratified beds.

In Tierra del Fuego Mr. Darwin describes the greater number of boulders as lying "on the lines of old sea-channels, now converted into dry valleys by the elevation of the land. They are associated with a great unstratified formation of mud and sand containing rounded and angular fragments of all sizes, which has originated in the repeated ploughing up of the sea-bottom by the stranding of icebergs and by the matter transported on them. Few geologists now doubt that those erratic boulders which lie near lofty mountains, have been pushed forward by the glaciers themselves, and that those distant from mountains, and embedded in subaqueous deposits, have been conveyed thither either on icebergs, or frozen in coast-ice."[2]

We have actual testimony as to the processes now in operation on the north-east coast of Labrador, and the capacity of coast-ice to polish rock-surfaces, and to produce boulder clay. Professor H. Youle Hinde[3] has described the action of "pan-ice," which is derived from bay-ice, floes,

[1] "Quart. Journ. Geol. Soc." vol. iv. p. 315.

[2] Darwin's "Voyage Round the World," 1860, p. 247.

[3] "Notes on some Geological Features of the North-Eastern Coast of Labrador," "Canadian Naturalist," New Series, vol. viii. p. 236.

and coast-ice, upon this coast; the pan-ice is formed by the breaking up of these sheets of ice during the storms of spring, and consists of large pieces or pans from 5 to 10 or 12 feet in thickness. "This broken ice is pressed on the coast by winds, and being pushed by the unfailing Arctic current, which brings down a constant supply of floe-ice, the pans rise over all the low-lying parts of the islands, grinding and polishing exposed shores, and removing with irresistible force every obstacle which opposes their progress. . . . . During a period of subsidence the blocks of strata, boulders, mud, and sand, pushed to and fro on the shallow sea-bottom by pan-ice, ultimately accumulate in hollows below its action, and when the débris is pushed into profound submarine valleys such as exist on the Labrador coast, the mass will resemble boulder clay, and in a sinking marine area it will accumulate to a great thickness. In a rising area it would be liable to be remodelled by the action of the waves, except in the case of very deep valleys."

The writer believes that this description indicates the manner in which the sheets of boulder clay that spread over such large areas in England have been formed. Coast-ice has ground down the material of the shores subjected to its action, and mixed up with it stones and boulders brought from other localities at a greater or less distance. It has pounded up the mass again and again, rounding the soft pebbles and breaking the harder, scratching and scoring both in the process. The whole British area was being gradually depressed so that every part of it was in turn subjected to the influence of the ice, which has by repeated shiftings moved some of the detritus from lower to higher levels in each locality, and left the whole country wrapped in a continuous sheet of boulder clay, which has only been partially removed by subsequent detrition.

With regard to the transporting powers of the ice in the same region, Sir Charles Lyell states, on the authority of Captain Bayfield, that the coast of Labrador between the latitudes 50° and 60° N., for a distance of 700 miles, is strewed over with ice-borne boulders. Some of the blocks were six feet in diameter, and all of them, both small and large, were being conveyed in the direction of the prevailing

current, viz., from north to south. Countless blocks were usually to be seen lying between high and low-water mark, but sometimes tracts of the coast were observed to be bare of boulders, and then again at another season thickly strewed with these erratics.

"Captain Bayfield saw similar masses carried by ice through the straits of Belle Isle, between Newfoundland and the American continent, which he conceives may have travelled in the course of years from Baffin's Bay, a distance which may be compared in our hemisphere to the drifting of erratics from Lapland and Iceland as far south as Germany, Belgium, and England."

Parts of the Baltic, such as the Gulf of Bothnia, where the proportion of salt in the water is only about a fourth of that in the ocean, are often entirely frozen over in the winter to a depth of 5 or 6 feet. Stones are thus frequently frozen into the ice along the shores; and, when summer comes, they are lifted up, and floated away on the ice-rafts (see p. 132). Professor Von Baer states that two huge blocks were transported by packed ice on the south coast of Finland, one of them being carried about a quarter of a mile, and left lying about 18 feet above the level of the sea.[1]

Dr. Forchhammer relates a remarkable fact which demonstrates how large a number of rock-fragments are annually transported by ice in the Baltic. A diver went down to examine a vessel, which had sunk near Copenhagen thirty-seven years before. He found the deck covered with blocks, from 6 to 8 cubic feet in size, and some of them piled one upon the other. He also affirmed that all other sunken ships in the Sound were covered with similar blocks.

Finally, if we consider the extensive areas in the northern hemisphere, over which coast-ice is now acting, and if we regard all the deeply indented coast-lines of Scandinavia, Greenland, and North America, every yard of which is more or less subject to this action, we shall conclude, with Professor Milne, that the coast-ice must, in quantity, be much greater than that of the glaciers, and much more

[1] Lyell's "Principles of Geology," tenth edition, vol. i. p. 385.

effective in the transport of rock débris. "All the vast ice-fields which break loose from the frozen regions of the North—and we read of them as 300,000 square miles in extent, and 7 feet in thickness—are in their passage south, driven in upon the land, and help to grind the coast-line, and transport its boulders. The northern field-ice, when it arrives in the latitudes of Newfoundland, is often seen to be covered with boulders, gravel, kelp, and other materials, showing it to have been, at some time or other, in contact with the coast." [1] The distance to which these materials may be transported is indicated by the southward extension of icebergs in the Atlantic.

[1] "Geol. Mag." Dec. 2, vol. iii. p. 408.

CHAPTER XII.

MARINE DEPOSITS (*continued*).

Chemical and Organic Deposits.

WE have next to consider what becomes of the mineral substances or salts which rivers hold in solution. Since nearly all the rivers of the world flow into the ocean, and nothing but pure water is taken out of it by evaporation, we should naturally expect to find that sea-water contained a large quantity of salts in solution. Everyone knows that this is the case. The average proportion of salts in the ocean is about 3½ parts in every hundred parts of water; and the average percentage of constituents, according to Bischof, is given in the following table:—

Chloride of sodium (common salt) . .	75·786
Chloride of magnesium	9·159
Chloride of potassium	3·657
Sulphate of lime (gypsum) . . .	4·617
Sulphate of magnesia	5·597
Bromide of sodium	1·184
	100·000
Total percentage of salts . . .	3·527

In the English Channel, the total percentage was found to be 3·551, and in the Mediterranean still higher, viz., 3·769.

From the above analysis it will be seen that the principal matters in solution are salts of sodium and magnesium, while the quantity of carbonate of lime, which is so universally dissolved in fresh water, is so small that it does not find a place in the analysis. Sea-water from Carlisle Bay, Barbadoes, is said to contain 10 parts of carbonate of lime in 100,000, and water from between England and Belgium, 5·7 parts in 100,000; and there is reason to believe that

it is always present, even in the waters of the Atlantic Ocean (see p. 213).

The smallness of the quantity to be found in sea-water, compared with that in almost all rivers, is doubtless owing to its being constantly abstracted in large quantities by marine animals, for the construction of their shells and other hard parts.

When we consider the vast number and variety of fish, of Mollusca, Crustacea, Echinodermata, and Actinozoa that inhabit the sea, and especially when we look at the enormous bulk of the coral reefs which are found within the tropics, we shall be in no danger of under-estimating the vast amount of carbonate of lime annually abstracted from the ocean. That it is abstracted more in one part than another, and that yet the ocean maintains a nearly equal average, will not be surprising, when we reflect on the extent of the great oceanic currents, and look upon all the seas and oceans as one vast slowly circulating system of moving water.

Another substance occurring in minute proportions in sea-water is silica. Forchhammer found it in all the specimens of sea-water which he analyzed, the greatest proportion being 3 in 100,000 parts of water.

The mineral substances above mentioned are extracted from the waters of the sea under certain conditions, and form deposits which are often of very wide extent. This extraction is effected in two ways:—(1), By means of evaporation, causing saturation and precipitation; (2), by means of organisms which take up silica or carbonate of lime to form their shells or skeletons. The subject of the present chapter, therefore, falls naturally into two sections—

1. Deposits formed by chemical precipitation.
2. Deposits formed by organic agency.

I. Chemically-formed Deposits.

Whenever portions of sea-water are separated by any means from the main body, so as to form isolated lakes or lagoons, the solution quickly becomes concentrated by evaporation, and some of the salts are precipitated.

Gypsum and Rock Salt.—In this process the point of saturation for sulphate of lime is much sooner reached than that for chloride of sodium; the former requiring only 37 per cent. of the water to be removed, and the latter 93 per cent. Gypsum, therefore, must always be deposited before rock-salt, and it is possible for this deposition of gypsum to take place without the point of saturation for rock-salt being attained. This may be the reason why, though the sea contains sixteen times as much salt as it does gypsum, that the latter more frequently occurs as a mineral deposit than the former, though it is not often found in such massive beds.

A good instance of the formation of gypsum beds from the concentration of sea-water is described by Professor Dana, as occurring in the dried-up lagoon of a coral island called Jarvis Island in the Pacific Ocean.[1] The flat surface of the central basin is covered with a deposit of guano, and underlying this is a stratum of sulphate of lime, frequently 2 feet thick, resting upon a bed of coral, sand, and shells. This deposit of gypsum is probably to be explained by the gradual elevation of the island, during which the lagoon waters were partially evaporated, but replenished from time to time by an influx from the sea, so that for a long time the condensation was not sufficient to precipitate chloride of sodium. Eventually, however, the whole was dried up, and salt was deposited, for around the lowest portion of the basin are incrustations of gypsum and common salt, ripple marks, and similar evidences of the gradually disappearing lake. Much of the salt may have been washed out by rain. Similar deposits of gypsum occur on many other elevated lagoons among the Pacific islands.

A good instance of the production of rock salt by the evaporation of sea-water is presented by the Bitter Lakes of the Isthmus of Suez. Before the construction of the Suez Canal the surface of these lagoons was far below the level of the Red Sea, and the evaporation of their waters had produced a bank of salt 66,000,000 square metres (16,000 acres) in extent, composed of layers which were

[1] Dana's "Coral Reefs," 1875, p. 251.

5 to 25 centimeters (2 to 10 inches) in thickness. It would appear that the lakes had been inundated from time to time by the waters of the Red Sea, while in the intervals between these incursions the evaporation and concentration was sufficient to precipitate a layer of salt, and so in time the large deposit above mentioned was accumulated.

In the dried-up lagoons of coral islands, crystal and beds of rock salt are frequently found (Dana).

Similarly in the limans of Bessarabia, on the Black Sea, which dry up in summer, we have the formation of salt beds going on before our eyes.

One of the *salinas* of South America is thus described by Mr. Darwin:—"The appearance of the country was remarkable, from being covered by the thick crust of common salt, and of a stratified saliferous alluvium, which seems to have been deposited as the land slowly rose above the level of the sea. The salt is white, very hard, and compact: it occurs in water-worn nodules projecting from the agglutinated sand, and is associated with much gypsum.

"The mine consists of a hard stratum, between 2 and 3 feet thick, of the nitrate, mingled with a little of the sulphate of soda, and a good deal of common salt. It lies close beneath the surface, and follows for a length of 150 miles the margin of a grand basin or plain. This, from its outline, manifestly must once have been a lake, or more probably an inland arm of the sea, as may be inferred from the presence of iodic salts in the saline stratum. The surface of the plain is 3,300 feet above the Pacific."

He also observes that "it is remarkable how all the circumstances connected with the salt-lakes in Siberia and Patagonia are similar. Siberia, like Patagonia, appears to have been recently elevated above the waters of the sea. In both countries, the salt-lakes occupy shallow depressions in the plains; in both, the mud on the borders is black and fetid; beneath the crust of common salt, sulphate of soda, or of magnesia occurs, imperfectly crystallized; and in both the muddy sand is mixed with lentils of gypsum. As these circumstances, apparently so trifling, occur in two distant continents, we may feel sure that they are the necessary results of common causes." [1]

[1] "Voyage of the 'Beagle,'" 1860, p. 67.

Dolomite.—In the contracting lagoons of certain coral islands, it appears possible for a compound of the carbonates of lime and magnesia (called Dolomite) to be formed. Analyses of the coral limestone of Matea have demonstrated that magnesia is largely present in some specimens of the rock, one specimen affording as much as 38 per cent. Dana thinks that this limestone must have been formed in a lagoon where the soft coral mud was mixed with a deposit of magnesian salts obtained from the sea-water as the solution became gradually concentrated by evaporation.

Dr. Sterry Hunt has suggested two chemical reactions, to explain the manner in which some magnesian limestones may have been produced:[1]—

1. If water containing carbonate of soda be mixed with sea-water, the salts of lime and magnesia which the latter contains are decomposed, and carbonate of lime, accompanied by a very small quantity of carbonate of magnesia, is at once precipitated. The greater part of the carbonate of magnesia remains in solution.

2. If water containing carbonate of lime be mixed with sulphate of magnesia, as in sea-water, a double decomposition takes places, producing carbonate of magnesia and sulphate of lime. On evaporation, the latter is precipitated as gypsum, and the former held in solution.

The result of both processes is to leave carbonate of magnesia in solution; and, if a further supply of carbonate of lime is added to this solution, further evaporation may cause a precipitate of the two carbonates, either in a state of intermixture, or in chemical combination. It is not quite certain whether the two ingredients would combine chemically to form a Dolomite; but it is known that magnesia has always a strong tendency to form double salts; and Sterry Hunt has observed that, *at the moment of its formation*, in a solution, carbonate of magnesia is quite ready to unite with carbonate of lime. If, therefore, we assume a continuous supply of the latter carbonate, under conditions where the evaporation is greater than the water supply (*i.e.* in lagoons or inland lakes), a true Dolomite may be formed.

[1] Other dolomites have been formed by the subsequent alteration of ordinary limestones, see Part II.

Carbonate of Lime.—Bischof states that there is five times as much free carbonic-acid gas in the sea as is necessary to keep in solution the quantity of carbonate of lime usually found in sea-water. This may be true of sea-water far from land; but near shore there are sometimes exceptional conditions. Thus, chemical precipitation appears to be possible near the mouth of a large river, which brings down much carbonate of lime in solution. It is, at any rate, a fact that hard, calcareous rock is being formed on the sea bottom opposite the mouths of the Rhone in the Mediterranean, and along the coast of Languedoc.

Lyell states that large masses of hard rock, consisting of sand cemented by calcareous matter, are continually found, and that a cannon, embedded in crystalline, calcareous rock, taken up from the sea near the river's mouth, may be seen in the museum of Montpelier.[1]

Deposits of the same kind are found along the southern coast of Asia Minor. Admiral Sir F. Beaufort found that great alterations had taken place on this coast since the time of Strabo: havens have been filled up, islands are joined to the main land, and many miles of new land have been formed, consisting of compact stone. Almost all the rivers and streams contain abundance of carbonate of lime in solution, and the precipitation of this binds together the sand and gravel in the river deltas, and converts them into calciferous sandstones and conglomerates.[2]

In accounting for this deposition of limestone, Lyell observes "that the fresh water introduced by rivers being lighter than the water of the sea, floats over the latter, and remains upon the surface for a considerable distance. Consequently, it is exposed to as much evaporation as the waters of a lake; and the area over which the river-water is spread, at the junction of great rivers and the sea, may well be compared, in point of extent, to that of considerable lakes."

It is probable, also, that a chemical action goes on where the under surface of this body of fresh water is in contact with the salt water. It has already been stated that carbonate of lime is more quickly precipitated in the presence

[1] "Principles of Geology," tenth edition, vol. i. p. 430.
[2] Op. cit. p. 431.

of an alkaline salt, such as sodium carbonate or chloride (see p. 176). If this is the case, we can easily understand that where a body of fresh water, containing much carbonate of lime in solution, enters the sea, and remains exposed to surface evaporation, a precipitation of the carbonate will take place. The formation of solid limestones, including marine shells, by a purely chemical operation, thus seems to be possible. The absence of marine currents, and the other conditions necessary for this process, may be seldom realized; but the view taken by some writers, that all marine limestones have had an organic origin, does not seem to be correct.

Moreover, it has recently been asserted by Herr Tornoe[1] that there is no uncombined carbonic acid at all in sea-water, and that the amount hitherto supposed to be present is really combined with lime. He founds this opinion upon two most important facts—

1. He states that sea-water has an alkaline, not an acid, reaction.

2. It appears that simple carbonates, in the presence of soluble salts of magnesia, are decomposed by continued boiling, with evaporation, the carbonic acid being set free.

He, therefore, concludes that if, as in ordinary analyses, the sea-water is boiled to evaporation, any carbonate of lime which may have been present will be decomposed, and will not be found in the residue. Finally, he states, as the result of many determinations, that there are as many as 97 milligrammes per litre of carbonate of lime in the waters of the Norwegian Atlantic (*i.e.* nearly 7 grains in the gallon), partly in the form of carbonate, and partly as bicarbonate. If this is so, it follows that the calcic carbonate can be precipitated under certain conditions.

In the neighbourhood of coral reefs, the waves wash out so much carbonate of lime from the coral rock that the sea-water is saturated with it, and the retiring tide will sometimes leave a thin white coating of it on the pebbles of the beach. Dana describes a beach on Oahu, one of the Sandwich Islands, where "the pebbles are covered with a thin incrustation of carbonate of lime, appearing as if they

[1] "Chemistry of the Norwegian North Atlantic Expedition."

had been dipped in milk, while others are actually cemented (together), yet so weakly that the fingers easily break them apart."

On the island of Ascension the rocks situated at the end of a long beach of calcareous sand are regularly coated every year with a white, thick, and hard deposit of carbonate of lime. Mr. Darwin describes another beach on the same island, and says: "The lower part of this, from the percolation of water containing calcareous matter in solution, soon becomes consolidated, and is used as a building stone."

"Similar aggregations are in progress along the shores of the whole West Indian Archipelago; in St. Domingo

A B

Fig. 42. Section of the Cliffs at Guadaloupe.
A, Ancient rocks. B, Recent limestone.

they have greatly extended the plain of Cayes, where accumulations of conglomerate occur, in which, at the depth of 20 feet, fragments of ancient pottery have been discovered. On the north-east of the mainland of Guadaloupe, a bed of recent limestone forms a sloping bank from the steep cliffs of the island to the sea. This rock is composed of consolidated sand and comminuted shells and corals: land shells, fragments of pottery, stone arrow-heads, carved stone and wooden ornaments and human skeletons, are occasionally found in it."[1] A slab of this rock, enclosing part of a human skeleton, is preserved in the British Museum.

[1] Mantell's "Wonders of Geology," seventh edition, p. 86.

Similar deposits of calcareous sandstone and conglomerate occur round the island of Ascension in the Atlantic.

II. Deposits formed by Organic Agency.

The power of aquatic animals to abstract some of the salts dissolved in the water they inhabit has already been mentioned. The lower and minuter kinds of animals make up for their smallness and apparent insignificance by their immense abundance, and this is true especially of those animals that live in the water, and most especially of those that live in the sea.

Some of these small animals secrete carbonate of lime, *e.g.*, the coral-forming Actinozoa or Polyps, and the small creatures known as Foraminifera. Others secrete silica, as the Radiolaria, which, like the Foraminifera belong to the sub-kingdom Protozoa, a division framed to receive all those small and simply-constructed animals with whose life-history we are not yet fully acquainted. All these forms of life produce mineral deposits of greater or less extent, which will be described in the following order:—

1. Calcareous Deposits. { *a.* Polyparian. *b.* Foraminiferal.
2. Siliceous Deposits. { *a.* Radiolarian. *b.* Diatomaceous.

1. *Calcareous Deposits.*

a. **Formation of Coral-Reefs.**—Coral-making Actinozoa exist in all temperate and tropical seas, and are found at various depths. The great *reef-making* corals, however, cannot exist in waters where the temperature ever falls below 68° F.; they are, therefore, confined to those parts of inter-tropical seas which are never invaded by currents of water colder than 68° F. Moreover, these coral polyps are not able to live at a greater depth than about 20 fathoms. In most localities where observations have been taken the limit at which reef-making corals were found alive was 15 fathoms. Another condition necessary for the growth of coral-reefs is clear water. Mud is always detrimental to animal life, and the coral-polyp is especially sen-

sitive to the influx of muddy water brought down from the land.

Even within the tropics the growth of coral reefs may be prevented by any of the following causes:—

1. The too great depth of the water.
2. The occasional influx of cold water.
3. The frequent influx of muddy water.

Since corals can only live in comparatively shallow water, from low tide level to about 15 fathoms, it follows that the reefs are generally formed along the margin of land. If the slope of the shore below water is steep, the reef is a narrow one, if the slope is gentle a wider fringe of reef will be formed, its outward extension being dependent upon the depth of the water. A reference to fig. 15 will make this evident.

The outer edge of the reef, then, as it runs along the shore, would be like a line of soundings in a chart, and mark the position where a certain depth occurs immediately outside it. This relation between the width of the surface of the reef and the depth of water outside it, when once established, leads to very important conclusions. These have been already mentioned in Chap. IV., and it was there shown that when the water outside a coral reef is very deep, we may safely conclude that the land has slowly sunk, and that the reef has grown continually upwards, the subsidence of the land never having been too rapid for the growth of the coral to keep pace with it. By the gradual subsidence of the land and the upward growth of the corals, fringing reefs are converted into barrier reefs, and the latter into Atolls. Hence Atolls or lagoon-islands, having originated from encircling barrier-reefs may be regarded as outline charts of the sunken islands upon which they have been reared.

Atolls are of all sizes, and almost all shapes, sometimes nearly circular, sometimes long and narrow, and varying from half-a-mile to 50 or 60 miles across. Such islands are entirely composed of coral-rock, the part above the sea-level consisting of coral-sand drifted up by the waves and winds, and subsequently consolidated into rock. The living reef outside is submerged at high water, but at low tide a broad, bare, rocky plateau is presented to view with pools

and holes, which swarm with molluscs and other animals; this plateau being often intersected and broken up by winding creeks and channels.

The seaward or windward side of coral reefs is always exposed to the battering and pounding action of the most tremendous surf, since the long roll of the ocean-swell falls suddenly upon the upper edge of the reef and dashes over its surface in huge breakers, that are sometimes felt even all across it. If a mass of coral, living or dead, be once detached from the rest, it is soon acted upon by these breakers, and ultimately triturated into calcareous sand.

The large solid corals, such as Porites, Astræa, and Mæandrina, grow chiefly along the outer margin of the reef where the breakers are continually rolling over them. The more delicate and branching forms, like Explanaria and Madrepora, flourish in the central lagoon, or in the more sheltered channels between the outer reefs. The top of the reef is often encrusted and heightened by a growth of calcareous seaweed called Nullipora, which sometimes forms a stony coating two or three feet in thickness, and serves to break the force of the waves.

The view of a coral-reef has been thus described by Mr. Jukes:[1]—"A coral reef is a very different, and in itself a much less interesting and beautiful object than I had expected; neither are the colours of the living corals so splendid as is often said. The mass of the reef is a dark-brown, close, hard rock, with here a patch of white sand, and there a lump or a mass of living corals, some of the smaller of which are grass-green, yellow, or red. When sailing among the islands, however, the reef and the islands often formed most beautiful objects, as seen from the poops, or mizen-top. The little island, crowned with trees, is surrounded by a smooth space of clear, shallow water of a bright, grass-green colour, round which is a narrow fringed margin of white foaming surf, sparkling in the sun, dividing the lagoon from the rich clear blue of the deep water outside."

The same author describes the composition of the solid reef-rock in the following terms:[2]—

[1] "Letters of J. B. Jukes," Chapman and Hall, 1871, p. 173.
[2] "Manual of Geology," third edition, p. 388.

"Coral reefs consist of living corals only in parts of their upper surface, and along their outside rim, which is a mere film compared with their whole bulk. All the interior is composed of dead corals and shells, either whole or in fragments, and the calcareous portions of other marine animals. The interstices of the mass are filled up and compacted together by calcareous sand and mud, derived from the waste and débris of the corals and shells and of countless myriads of minute organisms, mostly calcareous also. The living part, even of the upper surface of the reef, is that only which is never dry at low water. The part which is then exposed is composed of mere stone, which is often capable of being split up and lifted in slabs, bearing no small resemblance to some of our oldest limestones. These slabs and blocks, when broken open, are frequently found to have a crystalline structure internally, by which the forms and the organic structure of the corals and shells are more or less disguised and obliterated. A coral reef, then, of which a part is still living and in process of formation above, may internally consist of solid crystalline limestone."

Upon this compact basis the wind often raises banks of calcareous sand derived from the waste of corals and shells, and these are compacted into masses which are very different from the lower portion of the reef. "The large fragments of corals and shells are never found much beyond the surf range of high-tide, and therefore always form rock at a low level; whilst, on the contrary, the fine calcareous sand is removed by the wind and deposited in irregularly laminated beds, which being consolidated in various degrees, are converted into rock of different qualities."[1] This consolidation is effected by the action of percolating rain-water, which dissolves some of the carbonate of lime from the surface layers and re-deposits it below in the form of a calcareous cement, so that the loose grains of sand are thus bound together into a solid mass. Captain Nelson describes the ordinary coral rock of Bahama as forming a strong and homogeneous calcareous sandstone, soft and loose near the surface, but harder

[1] Nelson on the Bahamas, "Quart. Journ. Geol. Soc." vol. ix. p. 206.

below, and capable of being used for building purposes. "It is somewhat similar to Portland stone in appearance, but softer and more porous. When first exposed it is quite white, but becomes of a dark ashen-grey colour along the sea-coast, and elsewhere when exposed to the weather. On some reefs the rock formed in this manner is distinctly *oolitic*, each particle being enveloped in two or three concentric coats, like the coats of an onion."

Fine mud is also formed by the further trituration of the sand, and is accumulated in the quiet waters of the internal lagoons and channels. Some of it is also carried out by the tides into the deeper water outside the reefs, and is spread over the bottom below the 20-fathom line, where it doubtless forms a thick deposit of fine calcareous mud, or ooze. Mr. Jukes states that wherever deep soundings were taken round the north coast of Australia, the "bottom" was found to consist of a very fine, almost impalpable, pale olive-green mud, which was entirely soluble in hydrochloric acid, and therefore consisted of carbonate of lime. It is probable that much of this material is obtained from the washings of the coral reefs, though a certain proportion may be of Foraminiferal origin, like the Atlantic ooze which will be presently described.

The soundings obtained by the "Challenger" expedition near the Bermudas in depths between 2,500 and 900 fathoms showed that in all cases the bottom consisted of "soft, white, calcareous mud, evidently produced by the disintegration of the Bermuda reef and of the multitude of pteropod shells which sink down from the surface." [1]

The same is the case in some of the inner channels and lagoons of the Bahama Islands, especially along the western coast of Andros Island, which is bordered by an extensive deposit of fine, chalky mud, thus described by Captain Nelson:[2]—"The western shore of the island is generally a stiff chalk-bank, four or five feet high, sloping inwards to the marshy chalk-flat which surrounds the fresh-water lake of Andros Island; at its eastern limit it abuts against a narrow ridge of hills along the centre of the islands.

[1] "Voyage of the 'Challenger,'" vol i. p. 289.

[2] "Quart. Journ. Geol." vol. ix. p. 208.

Parallel to the western coast and seaward, with a breadth of 14 or 15 miles, the chalk continues in mass as an anchorage," and beyond this it is spread out as a thin covering over the sandy bottom for a space of about 80 miles in length by about 60 in extreme width, the area being rudely heart-shaped.

The thickness of some of these limestone rocks must be very great. Soundings have been made outside many Barriers and Atolls, proving that in many cases they spring from depths of 200 to 300 fathoms (1,200 to 1,800 feet). Dana states that outside some Atolls in the Pacific a depth of 600 fathoms, or 3,600 feet, was found at a distance of only one mile from the shore, but these may have been reared upon submarine volcanoes.

Neither is this formation of limestone confined within small areas. In the Pacific Ocean there is a continuous band of coral islands, which, measuring from the south end of the Low Archipelago to the northern termination of the Marshall Islands, is 4,500 statute miles long, and varies from 200 to 600 miles broad; to which may be added, the Caroline and Pellew Archipelagos, stretching more than another 1,000 miles to the westward. The Barrier reefs on the north-east coast of Australia are 1,250 statute miles in length, and from 10 to 90 miles in width.

These areas form a space including something like a million of square miles, over which carbonate of lime has been extracted from the sea and consolidated into great sheets and banks of limestone, which may be in some places over 1,000 feet thick. The limestones thus formed may be coarse and shelly, or they may be fine and compact, they may resemble coarse ragstone, oolitic freestone, or the finest chalk, according as they have been consolidated from the reef rock, the beach sands, or the oozy mud derived from the detrition of the reefs.

b. **Foraminiferal Deposits.**—All the marine deposits which we have hitherto described are taking place in comparatively shallow water and in the immediate neighbourhood of land, from the destruction of which, or of the coral reefs which border its coasts, the materials of the several kinds of sediment are derived. Deposition, however, is not confined to these regions, for extensive formations are being accumulated over the beds of the deepest oceans

through the agency of the minute organisms known as Foraminifera (see fig. 42).

These little animals exist in countless myriads in all warm and temperate seas, and the calcareous shells which they produce are of the most varied and beautiful forms. They generally consist of several chambers, each of which is perforated by numerous holes, through which the delicate tentacular processes of the animal are protruded.

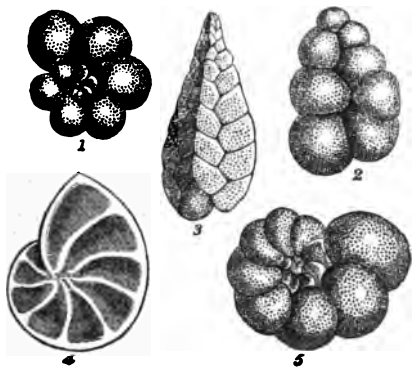

Fig. 43. Foraminifera, highly magnified.
1. Globigerina. 2. Textularia. 3. Verneuilina. 4. Cristellaria. 5. Rosalina.

The deep-sea soundings carried out across the North Atlantic by Captain Dayman (1857), and more recently by the officers of the "Challenger" expedition (1873-6), have made us acquainted with the bed of that ocean more completely than any other. At a distance of about 200 miles from the west coast of Ireland the bed of the Atlantic slopes down rapidly to a depth of 1,700 fathoms, and thence there is a great undulating submarine plain which extends to within 500 miles of Newfoundland, when the bottom slopes gradually up again till it rises into dry land. This great plain has been called the telegraphic plateau; from east to west it measures about 1,300 miles, and from Greenland on the north to the Azores on the south its extent is about the same, most of this space being about 2,000 fathoms deep, and no part of it being deeper than 2,700 fathoms, or 16,200 feet.

Specimens of the mud at the bottom were brought up by the sounding machines during the various surveys, and that which is found all over the central space between Ireland and Newfoundland, and also far to the southward, is a kind of soft sticky or mealy substance, which was described by Capt. Dayman under the name of ooze. This ooze is of a whitish, or greyish-white tint, and when dry resembles very fine chalk. When examined under the microscope it is found to consist chiefly of the shells of Foraminifera, and as more than three-fourths of these belong to the one genus *Globigerina*, it has therefore been termed the *Globigerina ooze*. When treated with a dilute acid, a violent effervescence takes place, and the greater part of its bulk disappears, being chiefly carbonate of lime. The insoluble remainder, usually about one-tenth by weight of the whole mass, consists partly of siliceous matter of organic origin, and partly of minute particles of quartz, felspar, and other minerals which occur in volcanic rocks. The transport of volcanic dust to great distances by the winds, and of pumice by marine currents, readily accounts for the occurrence of these mineral fragments. The shells and skeletons of various marine animals also occur in the ooze.

The analyses of Globigerina ooze vary considerably, but the following is the composition of three samples,[1] one from the depth of 1,900 fathoms in the North Atlantic (1), and the second from a depth of 1,420 fathoms (2), the third from 450 fathoms:—

	No. 1.	No. 2.	No. 3.
Loss on ignition . . .	6·63	3·80	4·00
Alumina and ferric oxide	5·86	4·42	4·80
Calcium sulphate . . .	0·51	2·82	1·00
Calcium carbonate . . .	74·50	80·69	84·27
Magnesium carbonate . .	1·27	0·68	1·28
Residue, chiefly silica . .	11·23	7·59	4·65
	100·00	100·00	100·00

[1] "Voyage of the 'Challenger,'" vol. ii. pp. 374, 380.

It was for some time a question whether these Globigerinæ lived at the bottom of the ocean where their shells are now found, or whether they lived in the surface waters, their shells only falling to the bottom when the animals died. The observations of Mr. Murray, during the voyage of the "Challenger," proved the latter to be the truth. He found that the Globigerinæ swarmed at and near the surface in such numbers that their shells must fall like an incessant rain through the waters of the ocean, and must be continually adding to the deposit at the bottom. Professor Huxley has calculated that if we assume this foraminiferal shower will form in one year a layer of solid matter one-tenth of an inch thick, "then if the present state of the Atlantic Ocean has existed for only 100,000 years, this apparently unimportant operation will have sufficed to cover its floor with the materials of a bed of limestone no less than 800 feet thick."[1] Looking only to the shallower parts of the Atlantic, where the deposits bear a greater resemblance to chalk than those of the deeper waters, we see that if these were gradually uplifted above its surface, the land so produced would consist of a chalky material similar to that which occupies so large a portion of the continent of Europe.

We have hitherto spoken only of the deposits in the North Atlantic, but the explorations of the "Challenger" expedition extended over the South Atlantic as well as the Pacific and Indian Oceans; from the published results of this survey, the following account has been compiled.

The exploration of the deeper parts of the ocean disclosed the remarkable fact that, while this white ooze is universally distributed over the bottom down to a depth of 2,000 or 2,200 fathoms, below these depths it passes into a deposit of very different character. The ooze becomes grey in colour, the tint deepening, and the shells in it assuming a more and more rotten appearance as the depth increases towards 2,500 fathoms, till it passes into a pure red clay, which consists almost entirely of a silicate of the red oxide of iron and alumina. This red clay occupies very large areas over the ocean bottom. Observations showed that

[1] "Physiography," p. 267.

the shells of the Foraminifera became more and more decomposed, and that the proportion of carbonate of lime in the ooze gradually diminished as the limits of the red clay were approached. It would appear, therefore, that the falling shells suffer from the dissolving action of the carbonic acid in the sea-water, and that where they have to fall through more than three miles of water they lose a large portion of their substance, and are finally altogether dissolved. It would also seem that this dissolution proceeds more rapidly at great depths, perhaps because of the great pressure at such depths, but the precise reason of this is not yet known. The origin of the materials which form the red clay is also a difficult problem, and the method of its formation is not yet completely understood.

The most probable explanations which have been suggested are:—

1. That a greenish silicate of iron and alumina, allied to glauconite, was first formed inside the shells, and that the red mud is the product of the disintegration of this material at great depths. (Dr. Carpenter.)

1. That it is the insoluble residue of the shells of Foraminifera and other organisms left by the removal of the carbonate of lime. (Sir Wyville Thomson.)

2. That it is the product of the ultimate decomposition of the pumice and other mineral fragments which are everywhere found in the ooze. (Mr. J. Murray.)

As a matter of fact, Mr. Murray finds that the proportion of recognizable mineral fragments is larger in the red clay than in the calcareous ooze, and he states that they are sometimes present in such abundance that their bulk is greater than that of the fine amorphous red-brown powder which forms the basis of the deposit. This, perhaps, might have been expected, since if we suppose that a rain of soluble shells and insoluble volcanic dust is taking place over the whole ocean, as appears probable, it is obvious that as the former are gradually dissolved the proportion of the latter will increase.

Perhaps we shall not be far wrong if we regard the red clay as the result of all the processes above mentioned, and consider it to be the fine mud produced by the

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gradual disintegration of felspathic minerals and of glauconitic grains, in addition to the minute quantities of similar material set free by the decomposition of organic bodies, and by the dissolution of their shells.[1]

2. *Siliceous Deposits.*

a. **Radiolarian.**—The Radiolaria inhabit all the warmer seas and oceans of the globe, and sometimes swarm in such numbers as to discolour the surface of the water. They can live at all depths, and different species are found to inhabit different zones of depth in the ocean, and certain forms have only been obtained from the bottom. Those most commonly met with belong to one of two groups, the *Polycistina* and the *Acanthometrina*. The former construct a delicate external shell like that of Foraminifera, only siliceous; the latter form an internal framework or skeleton of siliceous spicules radiating from a central point.

The tests of Polycistinæ occur in all deep-sea deposits, and were especially abundant in the deepest soundings examined by the staff of the "Challenger" expedition. Thus, from the depth of 4,575 fathoms in the Pacific, a fine gritty reddish deposit was obtained, which proved to be so largely composed of Radiolarian tests that Mr. Murray proposed for it the name of *Radiolarian Ooze*. This siliceous ooze is always mixed with a certain amount of red clay previously described, and it is now believed that below a depth of about 3,000 fathoms the red clay in the Pacific Ocean begins gradually to alter again by the increasing proportion of Radiolarian tests, until at extreme depths it passes into this Radiolarian ooze, contrasting with the Globigerina ooze in being siliceous instead of calcareous.

Sir Wyville Thomson observes that "if the Radiolarians live at all depths in the sea, the number of their skeletons falling to the bottom at one place must increase with the increasing depth of the water, and it becomes quite intelligible that, in a bed which is being formed at the prodigious

[1] The hypotheses given in the text regarding the formation of the calcareous ooze and the red clay cannot be considered as established, and may be modified by future examination and research.

depth of five and a half nautical miles, the tests of the Radiolarians should so preponderate over the red clay as to entirely alter the character of the deposit." [1]

In Barbadoes there is a siliceous deposit composed of the skeletons of Polycistina, which extends over a large area, and attains a considerable thickness. The siliceous particles are more or less united together by a calcareous cement, and the material known to microscopists by the name of Barbadoes earth.

b. **Diatomaceous.**—The lacustrine forms of the microscopic plants called Diatoms have already been mentioned (p. 181). We are now concerned with those which live in salt water. They abound in all seas from the equator to the poles, and have been found alive in ice. According to Ehrenberg, the siliceous cases of these organisms which are annually deposited in the harbour of Wismar, on the Baltic, amount to about 18,000 cubic feet, and the mud there formed is consequently very siliceous. Ehrenberg has also shown that the finest marine silts and muds, especially such as are deposited in estuaries, contain large numbers of Diatom frustules, and Radiolarian tests.

Sir Wyville Thomson states that in some parts of the Indian Ocean they form the bulk of the sample brought up by the sounding machine. The siliceous deposit which must here be in process of formation may therefore be termed a *Diatom ooze*.

Sir John Hooker mentions their abundance in the South Polar Ocean, and describes a diatomaceous ooze as occurring near the Victoria Barrier over an area measuring about 400 miles in length and 200 in breadth.

It is not surprising, therefore, to find that these siliceous deposits form extensive beds in some parts of the world. The town of Richmond, Virginia, U.S., is built on siliceous marls having such an organic origin, and forming strata 30 feet in thickness. In these beds the beautiful microscopic objects, *Actinocyclus* and *Coscinodiscus* are found, as well as several species of *Navicula* and *Galionella*, some of which are shown in fig. 44. These earths occupy con-

[1] "Voyage of the 'Challenger,'" vol. i. p. 238.

siderable districts, spreading out into sterile tracts along the flanks of the hills, their siliceous character rendering the soil unfit for cultivation.

Glauconitic Sands.—In some localities the dead shells of the Foraminifera lying on the bottom are found to be filled with a green silicate of iron, potash, and alumina, known by the name of *Glauconite*. In other places internal moulds or casts of such shells occur, formed of a similar material; and these are accounted for on the supposition

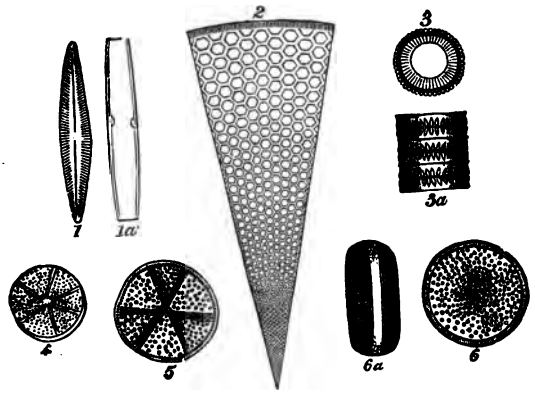

Fig. 44. Diatoms from the Richmond Earth.

1. Navicula.
2. Coscinodiscus radiatus.
3. Galionella sulcata.
4, 5. Actinocyclus (two species).
6. Coscinodiscus patera.

that the calcareous shell which they filled has been removed by the process of solution already mentioned (p. 224).

Mr. Murray states that these green casts of Foraminifera are found most abundantly at the bottom of comparatively shallow water, viz., from 100 to 700 fathoms, and that in all cases where they occur, particles of glauconite are also numerous. Beyond 700 fathoms neither casts nor glauconite grains are often found, and when they do occur it is only in small numbers. Both of them, therefore, appear to be formed under the same conditions.

Along the line of the Agulhas current the grains of

glauconite were so numerous as to form a regular bed of green sand on the bottom. During the explorations of the "Challenger" glauconite was more especially noticed off the coast of Portugal, and in grey mud at 600 fathoms off the Crozet Islands in the Southern Ocean, where the casts were of a pale straw colour, unaccompanied by any grains; and again off the east coast of Australia, in 400 fathoms, where the casts were dark green, light green, and dirty white. In some cases the smaller chambers of the Foraminifera had been filled with green glauconite, and the larger cells with a white or greyish silicate.

Glauconite grains are of frequent occurrence in rocks of all ages, and certain beds called Greensand consist of sandy or marly matter in which so many glauconite grains are distributed as to impart a green colour to the mass. Ehrenberg long ago demonstrated that most of these grains were casts of Foraminifera, and this is confirmed by the observations above mentioned. It is possible that some of the larger and more irregularly-shaped grains may be fragments of the casts formed in larger shells, such as some of the Pteropodous Mollusca; these shells always accompany those of the Foraminifera on the ocean bottom, and their casts in green earth have likewise been met with.

Mr. Sorby, in the course of his microscopical investigations, has found glauconite in the cells of Foraminifera, in the hollow spaces in the tissue of corals and Echinoderms, in holes bored into shells, and, in fact, in all kinds of cavities. Sometimes it occurs in the form of rounded grains or angular fragments which seem to have been formed elsewhere and drifted as sand into their present position.

Absence of Oceanic Deposits among Stratified Rocks:—Although in this chapter some account has been given of the peculiar deposits which are now being formed on the bed of the deep oceans, it is desirable to point out that an acquaintance with these accumulations is of less importance to the geological student than a knowledge of the mode in which deposits are produced in shallower waters. His observations would soon teach him the close analogy which exists between ancient shales, sandstones, and conglomerates, and the most recent deposits of mud, sand,

and gravel which he can examine round our coasts, and he cannot fail to perceive that they must have been formed under similar conditions. He will find also many beds of limestone which are evidently made up of the débris of corals, shells, and Echinoderms, and are therefore similar in composition to the limestones which are now being formed in the neighbourhood of coral-reefs.

He might, however, travel over large tracts of the earth's surface without finding any rock which is analogous in composition to that of the deep-sea muds above described. The only rock in England which gives any evidence of having been formed under oceanic conditions is chalk. As already stated (p. 222) there is a considerable amount of resemblance between chalk and calcareous ooze; both consisting principally of carbonate of lime, and both containing the shells of Foraminifera in abundance. Here, however, the resemblance ends; there is every reason to believe that the calcareous matter of the ooze has resulted from the disintegration of Foraminifera, but very many of the minute particles which make up the mass of the chalk have been derived from the decomposition of various shells. Mr. Sorby remarks[1] that "though the shells of Foraminifera are a very important constituent, yet other larger calcareous organisms have probably yielded the greater part of the rock. It is therefore very far from being identical with the Globigerina ooze of our modern deep oceans, though there is an interesting connection between them."

The chemical composition of different kinds of chalk will be best understood from the following analyses:—

[1] "Address to Geol. Soc. of London, 1879," p. 48.

	I.[1]	II.	III.
Carbonate of lime	94·09	97·25	98·52
Carbonate of magnesia. . .	·31	trace	·29
Sulphate of lime	—	—	·14
Chloride of lime	1·29	—	—
Alumina and peroxide of iron	traces	1·26	·40
Moisture and organic matter	·70	·45	traces
Residue, chiefly silica . . .	3·61	?	·65
	100·00	98·96	100·00

If these analyses are compared with those of the calcareous ooze given on page 222, it will be seen that the proportion of carbonate of lime is very much greater in the case of the chalk, and that of the silica much less. Now it has been stated that the proportion of calcic carbonate in the ooze decreases with the depth of the bottom from the surface, while samples taken from places where it lies on bottoms of less depth than 500 fathoms contain the largest amount of calcic carbonate, and thus approximate to the chalk in composition. It is only reasonable to conclude that the chalk was deposited in a sea of less depth than 500 fathoms, though doubtless at a considerable distance from land.

The student therefore will do well to remember that though the sediments of calcareous ooze, red mud, and radiolarian ooze, which are now being formed beneath the oceans, are interesting cases of modern deposits, yet they cannot be regarded as specially illustrative of the formation of such rocks as are met with in those parts of the earth's crust to which we have access.

[1] I. is from the grey chalk of Folkestone, II. from the chalk-rock of Cambridgeshire, III. from the upper chalk.

PART II.

STRUCTURAL GEOLOGY,

OR THE STRUCTURE AND RELATIVE POSITION OF ROCK-MASSES.

THE geological significance of the principal physical operations which are now taking place in or upon the earth's crust has been considered in the first part of this volume. The knowledge thus obtained will enable us to explain the nature and structure of the various rock-masses which make up that portion of the earth's crust that is open to our observation; and to understand how the rocks have been brought into the positions in which they are now found.

When the student is in possession of these facts he is able to enter upon a third branch of geological inquiry, namely, that of Physiography, or the evolution of the physical features of the earth's surface.

SECTION I.—Lithology.

CHAPTER I.

CRYSTALS AND ROCK-FORMING MINERALS.

IN the preceding pages we have assumed that the reader possesses such an acquaintance with the commoner kinds of rock as may be obtained from any elementary treatise on Geology or Mineralogy. To comprehend what has gone before it was only requisite that he should understand the difference between such common materials as clay, chalk, sandstone, limestone, granite, &c.; but before entering upon the special study of rock-masses, it is certainly necessary to have a more considerable acquaintance with the different kinds of rocks and minerals which occur in the earth's crust. The following chapters have therefore been prepared with the object of imparting to the student just so much mineralogical information as will enable him to comprehend the contents of those that succeed them.

Lithology, or the study of the mineral components of rocks, is based on the science of mineralogy. It is not necessary, however, for geological purposes that the student should make himself acquainted with all the different minerals known to the mineralogist, because those which may be considered as the *essential* constituents of rocks are comparatively few in number. It is therefore only these special rock-forming minerals which will be described in the following pages.

Again, to understand mineralogy some knowledge of chemistry is required, and if the student has not previously acquired this, it will be desirable for him to read some elementary treatise, such as Roscoe's "Primer of Chemistry" (Macmillan's Series, price one shilling). Chemistry and Mineralogy being equally outside the scope of

this manual, we shall not occupy space by giving more than a brief summary of what the student can learn elsewhere.

Chemical Elements and Compounds.—Chemical analysis has discovered that there are between sixty and seventy simple or elementary substances. All mineral bodies and all organic bodies consist either of one of these elements, or of a compound of two or more of them. Except fifteen these are all metals, and of these metallic elements many are of very rare occurrence. Of the other fifteen some are solid, as sulphur and carbon, others are always found in a gaseous state, such as oxygen, hydrogen, and nitrogen.

Of all these elementary substances not more than nineteen enter into the composition of rock-forming minerals; these are given below, together with the letters which chemists employ to denote them.

Non-Metals.		Metals.	
Oxygen	O	Aluminium	Al
Hydrogen	H	Potassium	K
Silicon	Si	Sodium	Na
Carbon	C	Calcium	Ca
Sulphur	S	Magnesium	Mg
Chlorine	Cl	Lithium	Li
Fluorine	F	Iron	Fe
Phosphorus	P	Manganese	Mn
Boron	B	Zirconium	Zr
		Titanium	Ti

Oxygen is the most abundant element on the earth. It combines with all the other elements except fluorine, and these simple combinations, or *oxides*, are consequently the most abundant and important compounds in nature. Oxygen combined with hydrogen, in the proportion of one atom of O to two atoms of H, forms water (H_2O). In combination with silicon it makes the substance silica (SiO_2), and combined with the metals aluminium, calcium, magnesium, it forms alumina (Al_2O_3), Lime (CaO), and magnesia (MgO). All these substances are oxides, and when they have no special name in ordinary use, like lime for the oxide of calcium, they are spoken of simply as the oxide of iron, or oxide of manganese.

It will be observed that the proportion of oxygen varies in different oxides, and some of the elements form two or more oxides which differ in appearance and properties; thus there are three different oxides of iron—viz., FeO, the protoxide; Fe_2O_3, the peroxide; and Fe_3O_4, an intermediate oxide.

Certain of the oxides of the *metals*, called *basic oxides*, combine with water to form compounds called *basic hydrates*, *e.g.* lime (calcium oxide) with water forms slaked lime (calcium hydrate); potassium oxide similarly yields potash (potassium hydrate). The basic oxides and their hydrates are collectively termed bases.

Most of the oxides of the *non-metallic* bodies, on the other hand, combine with water to form compounds, called *acid hydrates* or *acids*, analogous in their composition to basic hydrates, but differing in their chemical properties. The simple acid-forming oxides are in this relation called anhydrides, *i.e.* bodies without water. Sulphuric acid and carbonic anhydride are examples of an acid hydrate and anhydride respectively.

These *acids* unite with *bases* to form compounds termed *salts*, water being at the same time produced. Salts are neither acid nor basic in character, and their formation consists in the replacement of the hydrogen of the acid by the metal of the base, the hydrogen thus set free uniting with the oxygen of the base to form water. The salts of the acids above mentioned are denoted by changing the termination "ic" of the acid into "ate," as carbonate, sulphate, silicate; thus, sulphuric acid and magnesia unite to form magnesium sulphate and water. In this case, sulphuric acid is the acid, magnesia is the base, and magnesium sulphate the resulting salt. The reaction is expressed graphically thus:

$$H_2SO_4 + MgO = MgSO_4 + H_2O.$$

Binary compounds, or the unions of two elements only, are then designated by the termination *ide*, and ternary compounds or unions, of at least three elements, are designated by the termination *ate*.

Salts can also be formed by the action of acid anhydrides on basic hydrates; and it is in this way that glass and

other silicates (salts of silicic acid) are produced. Thus, if silica is heated to a high temperature with potash or soda, they will unite, and form a liquid which, on being cooled, solidifies into the transparent substance known as glass. The silicates of alumina, magnesia, lime, and iron are the principal constituents of one class of rocks.

Crystallography.—A crystal is a regular geometrical solid, the external form of which is dependent on its internal structure. All crystalline bodies are so symmetrically constructed that they split readily in certain directions, and this splitting is called crystalline cleavage. The surface planes of crystals have definite relations to certain imaginary lines, which are assumed to intersect in the centre of the crystal, and to join opposite similar parts, such as opposite angles, or the centres of opposite faces. These lines are called *axes*, and, in most instances, it is

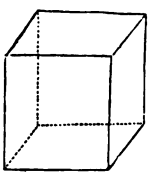

Fig. 45.

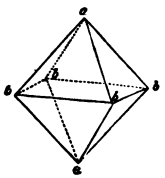

Fig. 46.

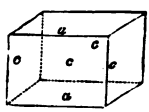

Fig. 47.

sufficient to select three of these symmetrical axes to express the ordinary relations of length, breadth, and thickness; but sometimes it is necessary to select four axes. The following are the six systems of crystallization which are ordinarily adopted:—

1. *Isometric or Cubic System.*—Three axes, all equal, and at right angles. Examples: The cube, with six square faces, as in fluor spar (fig. 45); and the octahedron, with its sides equilateral triangles, see fig. 46.

2. *Tetragonal or Pyramidal System.*—Three axes at right angles, but only two of them equal. Examples: The rectangular prism on a square base (fig. 47); and the octahedron, with its sides isosceles triangles, as in fig. 48.

3. *Hexagonal or Rhombohedral System.*—Four axes, three equal and crossing each other at angles of 60° in the same

plane, the other perpendicular to this plane. Examples: The six-sided prism on a hexagonal base (see fig. 49), or terminated by a six-sided pyramid, as in quartz.

4. *Rhombic or Prismatic System.*—Three unequal axes, at right angles. Examples: The rhombic prism (fig. 50), and the rhombic octahedron (fig. 51).

5. *The Monoclinic System.*—Three unequal axes, two at

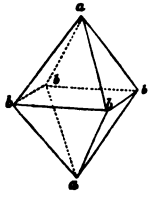

Fig. 48.

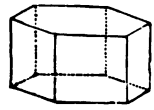

Fig. 49.

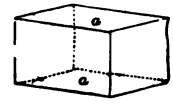

Fig. 50.

right angles, and one at right angles to one *only* of these. Example: The oblique rhombic prism (fig. 52).

6. *Triclinic or Anorthic System.*—Three axes, all unequal, and oblique to each other. Example: The doubly oblique prism (fig. 53).

The diversity of forms presented by natural crystals is almost infinite; but they may all be referred to one or

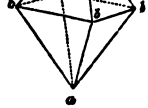

Fig. 51.

Fig. 52.

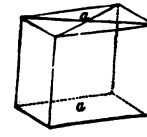

Fig. 53.

another of these systems, and may be actually produced by a modification of one of the typical forms above mentioned. Thus, in the first system, a regular octahedron can be obtained from a cube in the following manner:—If the eight corners of a cube be regularly truncated, or cut off, as indicated in fig. 54, eight new faces will be produced, resulting in fig. 55; and if the process is continued by cutting

away equal portions from these new faces, until the planes meet or touch each other, the regular octahedron will be developed, as shown inside fig. 56.

Similarly, other varieties of form may be produced by the partial or complete truncation of the sides of a cube or octahedron. Thus, if the twelve edges of an octahedron be truncated, we have the form of fig. 57; and, if this truncation be continued till the planes intersect, it will result in the formation of a regular twelve-sided figure, called the rhombic dodecahedron (fig. 58).

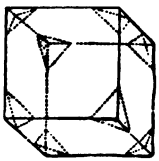

Fig. 54.

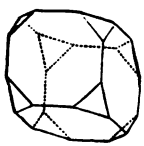

Fig. 55.

Fig. 56.

But, if the eight corners or angles of the octahedron are truncated, the cube is produced, as shown in fig. 59. Thus, all three forms may be developed from each other; and similar relations exist between the forms of other systems.

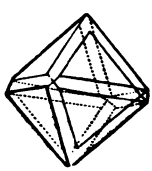

Fig. 57.

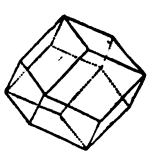

Fig. 58.

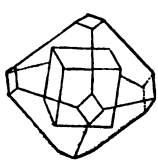

Fig. 59.

Other forms are produced by the combination or interference of two or more crystals. Double crystals are called *twins*. Some twins are composed of two half-crystals, twisted half round on a common axis. Some form an angle with each other like a knee-joint, and are hence called genicular twins; and double genicular twins, thus composed of four half-crystals, sometimes form perfect crosses, which are characteristic of certain minerals.

Pseudomorphs.—Pseudomorphism is the occurrence

of one mineral in the crystalline form of another mineral. This may take place either by alteration or substitution. In the one case, the first mineral has been gradually changed into another by the addition or exchange of constituents. In the second case, the new mineral is formed in the mould left by the total removal of the first mineral. Both processes are accomplished by the action of carbonated water, containing solutions of various minerals obtained from the rocks through which it has percolated. Penetrating deeply into the earth, acquiring a higher temperature, and helped by pressure, such water becomes an active agent in altering the constitution of minerals and rocks.

Some of these changes have been imitated in the laboratory of the chemist. Thus "Stein converted a crystal of gypsum (sulphate of lime) into carbonate of lime by leaving it for several weeks in a solution of carbonate of soda at a temperature of 122° F."[1] The sulphuric acid of the gypsum united with the soda to form sulphate of soda, which was dissolved and carried away by the water, while the lime united with the carbonic acid, and remained in the crystalline form of gypsum. The result is only attainable under certain conditions, of which the most essential is slow action, otherwise the original form is lost; but these conditions are eminently fulfilled in all natural operations. The process by which such an alteration-pseudomorph is produced is a very important one, since it is precisely that of *petrifaction*, or the mode in which organic forms are mineralized, and their external form, with more or less of their internal structure, preserved for our examination. It also explains the manner in which many metamorphic rocks have been produced, since the formation of a pseudomorph is in fact a process of transformation, or metamorphism.

So important and instructive are some of Bischof's remarks on this subject that we quote the following passages at length:—

"As petrifactions are important, and in many cases indispensable aids in recognizing the sedimentary formations,

[1] Bischof, "Chemical Geology," vol. i. chap. ii.

so likewise pseudomorphs are important, and frequently the only means of tracing the processes of alteration and displacement which have taken place and are still going on in the mineral kingdom."

"In the analysis of a mineral in which changes have already commenced, especially by the addition of new constituents, it is not unlikely that they may be considered as accidental, and deducted." Since, however, the alteration is seldom one of simple addition, but takes place by removal and replacement, the new constituents must be considered as representing portions of the original constituents, lost and replaced by pseudomorphs. Thus "there are sufficient grounds for considering andalusite to be a pure silicate of alumina, although previous analyses have pointed out, besides these two essential constituents, potash, lime, magnesia, oxides of iron and manganese and water. Andalusite is converted into mica, in which change a part of the alumina is removed; potash, magnesia, and peroxide of iron being introduced into its place. One of these bases is always found in andalusite, sometimes several of them together; and it may therefore be inferred that this mineral, as usually met with, is already in a state of incipient alteration."

"These examples will suffice to show the importance of the minute quantities of substances present in minerals and *generally* considered *as accidental*. These substances, which are troublesome to the chemist, because he cannot introduce them into the chemical formula, acquire significance when compared with the constituents of the pseudomorphs resulting from the alteration of the mineral in question. They then no longer appear as accidental, but indicate the transition of one mineral into others, and lay before us clearly the greater part of the conversion process."[1]

Rock-forming Minerals.—We now proceed to describe those minerals which are the essential constituents of rock-masses. Of the simple elementary substances mentioned on page 234, two only are ever found as minerals, viz., carbon and sulphur. The latter never occurs as a rock-constituent, though it is sometimes rather abundant

[1] Bischof, "Chemical Geology," vol. i. chap. ii.

near volcanoes; the former occurs as a constituent of coal, and as graphite in schist and gneiss. All other minerals are compound substances, and are either binary or ternary combinations, which may be classified in the following manner:—

Binary compounds: A. oxides, chlorides, fluorides.

Ternary compounds: B. Carbonates, sulphates, phosphates. C. Silicates (anhydrous). D. Silicates (hydrous).

Minerals formed of Binary Compounds. (A.)

Quartz is crystallized silica (SiO_2), is often called rock-crystal, and sometimes Irish diamond, Bristol diamond, &c. The crystals belong to the hexagonal system, their most usual form being a six-sided prism terminated by six-sided pyramids, see p. 237; they are sometimes very large, and sometimes so minute that the mineral appears to be a compact hard stone, which is milk-white when pure. Amethyst, agate, chalcedony, carnelian, onyx, cat's-eye, bloodstone, are all mere varieties of quartz, stained of various hues by slight admixtures of iron, manganese, or other colouring matter. Flint and chert are also impure varieties of silica, generally minutely crystalline.

Opal and its varieties are hydrated and non-crystalline forms of silica. One of these varieties, called menilite, occurs in the form of concretionary nodules, like the flints in chalk. The hydrated form of silica precipitated from thermal waters is called sinter or geyserite; its mode of occurrence has already been described, page 150.

When quartz occurs in an igneous rock it is usually a greyish, semi-transparent, glassy-looking, irregularly crystalline granule, which cannot be cut or scratched by even the best steel knife.

Oxide of Iron.—Two oxides of iron occur as minerals, the peroxide or sesquioxide (Fe_2O_3), and the less highly oxidized Fe_3O_4.

Hæmatite (Fe_2O_3) is red or black in colour, but always gives a blood-red streak. When distinctly crystallized it

is called specular iron, and belongs to the hexagonal system, and usually occurs in thin tabular crystals, or scales. It often forms fibrous nodules, but many of the beds and nodules of red iron ore which occur among the stratified rocks have resulted from the decomposition of carbonate of iron by the action of water, and hæmatite is therefore frequently a pseudomorph of chalybite. Under the microscope it usually appears in the form of red flecks or scales.

Limonite is a hydrated form of hæmatite, with the formula, $2Fe_2O_3$, $3H_2O$, and generally having a yellowish-brown colour. Yellow ochre and bog-iron ore are varieties.

Magnetite (Fe_3O_4), so called from its magnetic properties, is usually black in colour and streak, and crystallizes in the cubic system, generally in some form of the octahedron. It sometimes occurs in a massive form; but is most frequently met with in igneous rocks, where it is disseminated in small crystals, always black and opaque, and presenting square or triangular sections under the microscope.

Ilmenite, a mixture of the oxides of iron and titanium, crystallizes in rhombohedral forms, and occurs generally in thin plates or tables, the outer parts of which are frequently decomposed into a greyish-white substance (Leucoxene).

Rock salt, or sodium chloride (NaCl), crystallizes in the isometric system, and generally in cubes; it is white when pure, but generally coloured red, blue, or purple. Rock salt occurs in extensive beds, which are sometimes of great thickness.

Fluor spar, or calcium fluoride (CaF_2), crystallizes in the isometric system, and usually in cubes, which are very variable in colour. It occurs chiefly in veins, and can hardly be called a rock-constituent.

Iron pyrites, or sulphide of iron (FeS_2), crystallizes sometimes in the isometric and sometimes in the rhombic system; when in the latter, it is called *marcasite*. It is generally of a light bronze colour, and is found disseminated in rocks of many kinds and all ages. In igneous and metamorphic rocks, it occurs in small, sparkling cubic or octahedral crystals. In stratified rocks, the marcasite or rhombic forms are, perhaps, more abundant, especially in

dark shales and clays. According to Ebelmen, pyrites is always formed wherever organic matter in process of decomposition acts on the sulphates of sea-water in the presence of ferruginous mud. Thus fossil organisms are often found coated or filled with iron pyrites; and the radiated globular nodules of marcasite frequently contain some small organic nucleus.

Its rôle as a metamorphic agent is not unimportant, for marcasite is readily oxidized, and a considerable quantity of sulphuric acid is set free in the process. This enables the water to dissolve other minerals, such as the silicates of alumina, and thus forms a solution which is a powerful agent of change. Dr. Sullivan states that the quantity of matter which sulphuric acid will enable water to dissolve is so great that the water pumped up from one mine in Ireland annually carries away more than 100 tons of silicate of alumina.

Ternary Compounds. (B.)

Calcite or calc-spar, carbonate of lime ($CaCo_3$), is, after quartz, the most abundant mineral in nature. Crystallized in the rhombohedral system, it is called *calcite;* but it also forms rhombic crystals, and is then known as *arragonite.* Calc-spar always cleaves readily into rhombohedrons; and the name of Iceland-spar is given to such as are clear, and possess the property of double refraction. *Stalactites* and *stalagmites* are formed of successive concentric films precipitated from evaporating water, and the radiating crystalline plates, which traverse these concentric coats, without obliterating them, show that the crystallization has been subsequent to their formation. *Calcareous tufa* has a similar crystalline structure, and *alabaster* is a hard, compact, semi-translucent form of tufa. *Dolomite* is a compound of the two carbonates of lime and magnesia; and when the mixture is crystallized, it is known as *bitter-spar.*

Calcic sulphate, or anhydrite ($CaSO_4$), is better known in the hydrated form of **Gypsum** ($CaSO_4$, 2H O), which usually crystallizes in monoclinic prisms. Gypsum, when

transparent, is called *selenite;* when fibrous, *satin-spar;* and some of the compact varieties are popularly called *alabaster*. It is only found in sedimentary rocks, occurring sometimes in veins and nodules, and sometimes in beds of great thickness, associated with rock-salt. Its formation from the evaporation of sea-water has already been noticed (p. 209). Crystals of selenite are abundant in many clays, either single, or in radiating groups.

Calcic phosphate is generally found as a tribasic salt, with the formula of Ca_3PO_4. When crystallized, it is called *apatite*, and occurs in six-sided prisms or tables, belonging to the hexagonal system. Small crystals are not unfrequent in igneous and metamorphic rocks. It is also found massive, forming beds several feet thick.

The phosphate nodules, so frequently found in stratified clays and marls, contain from 30 to 60 per cent. of tribasic phosphate of lime, mixed with carbonate of lime and other earthy materials.

Anhydrous Silicates. (C.)

The Felspars are a family or group of minerals which play a very important rôle in the constitution of rocks. They all consist of silicate of alumina, combined with the silicates of potash, soda, or lime. The names of the most important Felspars are given in the following table, together with their average composition :—

	Silica.	Alumina.	Potash.	Soda.	Lime.	Sp. Gravity.
Orthoclase .	64·6	18·4	16·9	—	—	2·55
Microcline .	64·3	19·6	15·6	—	—	2·54
Albite . .	68·6	19·5	—	11·8	—	2·62
Oligoclase .	62·1	23·7	—	10·2	4·0	2·64
Andesine .	59·7	25·6	—	7·7	7·0	2·66—2·69
Labradorite .	52·9	30·3	—	4·5	12·3	2·68—2·74
Anorthite .	43·1	36·8	—	—	20·1	2·75

Orthoclase and Microcline are, therefore, Potash Felspars; Albite is a Soda Felspar; Oligoclase and Andesine are Soda-

Lime Felspars; Labradorite is a Lime-Soda Felspar; Anorthite is a Lime Felspar. The first two are the lightest, and the last is the heaviest. One only (Orthoclase) crystallizes in the Monoclinic system, all the others belonging to the Triclinic system; hence the group is sometimes divided into the Orthoclastic and the Plagioclastic Felspars. It has been supposed by some that Oligoclase, Andesine, and Labradorite are not distinct species, but mixtures of Albite and Anorthite in varying proportions.

Orthoclase Felspar generally occurs as a translucent, or semi-opaque, mineral, of a white or flesh-red colour, in monoclinic crystals of an oblong shape, which are frequently twinned. When transparent, with a pearly opalescence, it is called *Andularia; Sanidine* is a similar transparent and glassy variety, forming crystals of a tabular shape, and chiefly occurring in volcanic rocks. *Perthite* consists of Orthoclase and Albite, in alternate layers, and presents a streaky pink and white appearance.

Plagioclase Felspars generally form long and narrow crystals, with a bright shining surface, and are usually white or greenish grey. Under the microscope, they may generally be distinguished from Orthoclase by the presence of fine parallel striæ (due to repeated twinning) along some of the planes of cleavage. These are never seen in Orthoclase.

Oligoclase and *Andesine* are usually whitish minerals, with a more or less vitreous lustre. The former is more frequently found in intrusive igneous rocks, and the latter only occurs in eruptive volcanic rocks. Oligoclase is usually composed of a number of long twinned crystals, which cause a well-marked striation.

Microcline resembles Orthoclase, but is triclinic, and *Amazonite* is a green variety of it, which was formerly referred to Orthoclase.

Labradorite is the commonest Triclinic Felspar, and forms masses of long twinned crystals, like those of Oligoclase; but usually grey, green, or brownish in colour, with a vitreous or pearly lustre. Labradorite is soluble in hydrochloric acid; but, under the microscope, it is difficult to distinguish it from Oligoclase, though the former often exhibits a number of fine parallel lines, which cut obliquely across the stripes of colour seen by polarized light.

Anorthite is a much rarer species, though it sometimes occurs in volcanic rocks, such as the vesuvian lavas. Being a very low silicated Felspar, it is possible to fuse it under the blow-pipe.

The lower silicated Felspars, Labradorite, and Anorthite are never found associated in igneous rocks with free quartz, because if there had been sufficient silica for the formation of quartz crystals, a highly silicated felspar would first have been formed. When, therefore, either of these felspars is found in company with quartz, we may conclude that the rock is a metamorphic and not a truly igneous rock,[1] and that the silica has only been partially fused. This is the case with the crystalline rocks of the Malvern Hills, which were formerly considered to be igneous.

Nepheline and **Leucite** are light-coloured minerals closely related to the Felspars, but crystallizing in different forms. The one occurs in rather stumpy six-sided prisms, and the other in icosi-tetrahedrons or solids with twenty-four faces. Their chemical composition is:—

		Nepheline.	Leucite.
Silica	=	44	56
Alumina	=	33	23
Potash	=	5	21
Soda	=	16	

Leucite is common in the lavas of Vesuvius, but has not been found in England, and Nepheline only in the rock called Phonolite.

The Micas are a group of minerals which vary much in composition, but have several properties in common. The crystals, whether belonging to the monoclinic or hexagonal system, split readily into very thin flexible plates, which have a bright pearly lustre and are more or less transparent. They are composed of a mixture of silicate of alumina with silicates of potash, magnesia or lithia, and some iron or manganese. They vary in their degree of fusibility, but are all easily scratched with a knife.

Muscovite, or Potash Mica, crystallizes in the rhombic

[1] As will be hereafter explained, an igneous rock is one which has crystallized from a state of fusion; a metamorphic rock is one which has undergone much mineral change.

system, and usually occurs in six-sided tabular crystals of a grey greenish or yellowish colour. It is very clear and transparent, and oftens forms large foliated masses, the separate plates of which are used instead of window glass in Siberia and elsewhere. Commercially it is known as talc, and is used for lamp-shades, &c., but the true talc is a different mineral.

Lepidolite, or Lithia Mica, may be regarded as muscovite in which the potash is partially replaced by lithia. Its physical properties are similar and its crystalline form the same, but it is usually rose-red or violet in colour, and commonly forms granular masses consisting of numerous scales or folia.

Lepidomelane, or Black Mica, is an iron-potash mica crystallizing in the hexagonal system, and occurring in small six-sided tabular crystals or in aggregations of small scales. It is found in some Irish and Cornish granites and its colour is black. *Biotite* is another hexagonal mica of a dark green or black colour, found in some gneisses and granites.

Hornblende and Augite.—Under these names are included a number of minerals which are closely related to one another, their essential composition being a mixture of silicate of magnesia with silicate of lime, the bases being often more or less replaced by iron or manganese. They all crystallize in the monoclinic system.

Common Hornblende is a dark green or greenish black mineral usually occurring in long prisms. The crystals frequently have a fibrous structure and a silky lustre, with angles of about 60° and 120°, properties which serve to distinguish them from crystals of Augite.

Augite generally occurs in short stout prisms, and cleaves readily along planes which are nearly at right angles to one another. The crystals are usually black, but there are white and green varieties, known respectively by the names of *Diopside* and *Sahlite*.

Pyroxene is another name for Augite, and *Amphibole* for Hornblende. There is good reason for supposing that they are identical minerals crystallized under different circumstances. Augite has been artificially formed in slags which cooled rapidly. Hornblende has never been so obtained,

and always occurs in rocks which must have cooled slowly. Hornblende has been observed in the thicker parts of a vein of lava exposed in the Val del Bove, Etna, while Augite occurs in the thinner parts of the same vein. Lastly, there is a mineral called Uralite, which has the outward form of Augite, but the cleavage and structure of Hornblende.

Diallage is a very cleavable variety of augite, generally having a pearly grey or brownish lustre; *Tremolite*, *Actinolite*, and *Asbestos*, are more or less fibrous varieties of Hornblende.

Hypersthene, *Enstatite*, and *Bronzite* are closely allied minerals, but differ in not containing lime, and in crystallizing in the rhombic system. They are all silicates of magnesia and iron: the first two are generally of a greenish or greyish brown colour; the latter is a dark yellow or brown with a bronze-like lustre, and has much resemblance to Diallage.

Andalusite is essentially a silicate of alumina, but always contains an admixture of the silicates of magnesia, potash, and iron. It crystallizes in the rhombic system, and the larger crystals are often encrusted with and penetrated by scales of mica, which may be a product of its decomposition. The variety *Chiastolite*, so called from the cruciform markings in the interior of the crystals, is usually met with in slates which have been partly metamorphosed by contact with, or proximity to, igneous rock. *Staurolite* is another alteration product, forming rhombic prisms which are frequently double genicular twins, forming a cross, whence its name. It consists of the silicates of alumina and iron.

Garnets consist of silicate of alumina with a silicate of some other base, such as lime, magnesia, iron and manganese. The percentage of silica is always from 35 to 40, and all the varieties crystallize in the cubic system, and usually in rhombic dodecahedrons. They are generally of a dark colour, red, brown, or black, and are of common occurrence in metamorphic and intrusive igneous rocks. *Idocrase* has a similar composition, but crystallizes in tetragonal forms, is usually lighter in colour, light brown, yellow, or greenish white.

Epidote is a silicate of alumina, lime, and iron; it crystallizes in the monoclinic system, and usually forms long blade-like crystals in radiating groups or nests of a light green colour. It is essentially an alteration product, and often forms little fringes around hornblende crystals.

Titanite (or **Sphene**) is a mixture of silicate of lime with titanate of lime, crystallizes in the monoclinic system, the crystals being usually thin, with sharp wedge-like edges. Its colour is generally brownish grey or yellow.

Peridote is a silicate of magnesia and iron, and is, therefore, chemically related to hypersthene and bronzite, but its physical properties are very different. It crystallizes in the rhombic system, and when found in transparent rhombic prisms it is often called *Chrysolite*, but it is much more abundant in the form of grains or granular masses of an olive or yellowish green colour; it is then known as *Olivine*, and is of frequent occurrence in certain igneous rocks, sometimes in such quantity as to be chief constituent of the rock called Peridotite.

Tourmaline, or Schorl, may be regarded as a combination of a silicate of alumina and iron with a borate. Their chemical composition is variable, but they generally contain: silica, 40 per cent.; alumina, 30 to 40 per cent.; boracic acid, 3 to 4 per cent.; with peroxide and protoxide of iron, and protoxide of magnesia. In colour it is greenish or reddish-black, and somewhat resembles hornblende, but may be distinguished by its more resinous fracture, the absence of distinct cleavage, and its frequent mode of occurrence in nests or masses of radiating crystals, which are prismatic forms of the hexagonal type. The black variety is of frequent occurrence in granites, which often become *schorlaceous* near their contact with other rocks.

Hauyne and **Nosean** are substantially silicates of alumina and soda, and are related to the garnets. The first is usually of a bright blue colour, and the second of a yellowish grey. They occur as constituents of certain basalts and phonolites.

Zircon, the silicate of Zirconium, belongs to the tetragonal system; the crystals are generally coloured red, yellow, or brown, and are of considerable hardness. It is found in syenite and other igneous rocks.

Silicates (*D.*) (*Hydrous*).

Talc is a hydrated silicate of magnesia and its percentage composition is generally as below:—

Silica	=	60 to 62
Magnesia	=	30 to 33
Water	=	1 to 7

When crystallized it is ortho-rhombic, but it usually occurs in a massive condition, splitting into thin laminæ, which are flexible, but not elastic as the plates of mica are. In colour it varies from white to apple-green. *Steatite* or *Soapstone* is a coarse earthy variety of talc, usually of a dull white or yellowish colour, and always found in a massive form. Both talc and steatite have a soft soapy feel. *Meerschaum* is a silicate of similar composition.

Serpentine is another hydrated silicate of magnesia, with the following composition in typical specimens:—

Silica	=	44
Magnesia	=	43
Water	=	13

It is generally compact and massive, of a dark green colour, and is greasy to the touch; but it varies much in colour, and is sometimes yellow, brown, red, or black, from the presence of iron. Serpentine, like steatite, results from the decomposition of magnesian minerals, and gives its name to a particular kind of rock, which is almost entirely composed of it.

Chlorite appears to be a hydrated silicate of magnesia and iron, with some sesquioxide of alumina; like all products of alteration, its chemical composition varies, but the following is the average percentage:—

Silica	=	30 to 34
Magnesia	=	32 to 37
Alumina	=	10 to 20
Water	=	12 to 13

Chlorite, like mica, is the name of a group rather than of a single mineral; it generally occurs in earthy or scaly

granules of a leek-green colour; sometimes it forms fibrous radiating crystals.

Glauconite is a hydrated silicate of iron, alumina, and potash, of a dull green colour; it is found in cavities of igneous rocks as a result of decomposition, and also occurs in the form of loose grains in marls and sandstones (see p. 227).

The Zeolites are hydrated double silicates having many varieties, to which separate names are given; most of them consist of silicate of alumina with silicates of lime, soda, or potash. They are, therefore, closely related to the Felspars, and may indeed be regarded as hydrated varieties of Felspar. The name Zeolite is derived from their intumescence or boiling up under the blow-pipe as the water is driven off. Mesotype, Prehnite, Chabasite, Analcime, Stilbite, and Thomsonite are among those most frequently met with.

CHAPTER II.

CLASSIFICATION OF ROCKS.

MEANING of the word Rock.—Before attempting to classify the various kinds of rocks which enter into the composition of the earth's crust, it is necessary in the first place to understand what geologists mean by the term rock. In ordinary language a rock means a hard and massive stone, but geologists know that the character of hardness is an accidental one. The very same beds of limestone may be soft chalk in one place and hard marble in another. The same beds of clay may be harder than the hardest brick in one place, and soft enough to mould into bricks in another. The same beds of sandstone may be hard grit in one part, while in another they could be dug out with a spade. Geologists apply the word "rock," then, as a general term, to any considerable mass of mineral matter, whether hard or soft, or whatever may be its form or character, provided it be of sufficient importance to be spoken of as a constituent part of the crust of the earth.

A rock, therefore, may be defined as a mass of mineral matter, consisting of numerous crystalline or fragmentary particles which may belong to one or several different kinds of minerals, and which may be loosely coherent or firmly compacted together.

Texture and Structure of Rocks.—The texture of a rock is the manner in which the component particles are arranged, so as to produce differences in the grain or texture. Texture, therefore, is a matter which can be determined from hand specimens, and is part of the study of Mineralogy or Lithology. The structure of a rock is the manner in which its different parts are built up into a rock-mass, so as to produce differences in the shape of the pieces or blocks into which it can be broken up. Structure therefore is a matter which can be best determined from

an examination of rocks in the field, and comes under the head of Petrology, or the study of rock-masses.

Lithological Classification of Rocks.—It is evident, then, that rocks may be classified either according to their textural or structural relations. Let us, in the first place, see to what conclusions a lithological arrangement would lead us. The words in which we have defined a rock suggest a primary lithological difference, whereby all rocks may be divided into two classes. Some are composed of definite *crystalline* particles, which, if not perfect crystals, yet possess some of the external faces and angles of perfect crystals, and have clearly been formed in the position which they now occupy. Other rocks consist of a congeries of particles which have not *grown together*, but are *fragments* which have been broken off their parent masses and *brought together* by some external agency; their coherence being caused either by mechanical compression or by a cement of some other substance.

By these lithological differences, therefore, rocks may be primarily distinguished into: 1, *Crystalline*; 2, *Fragmentary*.

Crystalline Rocks.—"All crystals are built up by the successive external addition of minute crystalline particles. It is clear, then, that these particles must have been free to move and arrange themselves; in other words, they must have been the result either of solution in water or other liquids, or of fusion by heat. Whenever, then, we find a crystal or a mineral particle that has an internal crystalline structure, we may feel assured that this structure has been produced either by solution or fusion; in other words, that the crystal has been either dissolved or melted. But if this be true as regards individual crystals, or crystalline particles, it must also be true of rocks that are made up of such crystals or particles." [1]

It has been already stated (see p. 68), that some minerals are soluble in water containing carbonic acid, and that under certain circumstances they may be deposited directly from such chemical solution. Other minerals, again, such as those which compose volcanic rocks, though practically insoluble in water, can be made fluid by the influence of

[1] Jukes' "Manual of Geology," 2nd Edition, p. 50.

heat. Crystalline rocks therefore are all chemically-formed, and are divisible into two sections—*a*, Aqueous crystalline rocks, and, *b*, Igneous crystalline rocks.

2. *Fragmentary Rocks.*—These consist of particles which have been derived from the disintegration and detrition of pre-existent rocks, or from the decay and disintegration of organic bodies. They may be divided into two groups or sections, according to the manner of their formation, viz., *a*, Mechanically-formed rocks; and *b*, Organically-formed rocks.

The particles of mechanically-formed rocks bear evident marks of mechanical fracture and attrition, most of them having been more or less rounded and worn by currents of water or of wind. This detritive and fragmental origin is very clear in the case of such rocks as are chiefly made up of pebbles or rounded fragments of other rocks, and is hardly less obvious in the case of sands and sandstones which have been derived from the continued attrition of such pebbles. Even igneous rocks have their mechanical accompaniments, in the shape of the dust, ashes, and fragments ejected from volcanic craters, and these may be compacted into solid rocks, whether they fall on the land or into the water.

The organically-derived rocks are wholly or in great part composed of fragments of the hard structures secreted by certain plants and animals, and the manner of their formation has already been fully described. The fragments may be little altered from their original condition or else they may be greatly altered and partly mineralized. In the latter case they become allied to the aqueously-formed crystalline rocks.

A lithological arrangement of rocks therefore results in our making four groups, thus:—

1. Crystalline { *a*. Aqueous. *b*. Igneous.
2. Fragmental { *a*. Mechanical. *b*. Organic.

This, however, is not quite satisfactory, for it classes together aqueous and igneous rocks, and separates the chemically-formed aqueous rocks from their closely allied

neighbours of organic origin. It is evidently, then, desirable that we should ascertain whether rocks do not exhibit some *structural* differences which are more closely in relation to the conditions under which they have been formed than their *textural* differences.

Petrological Classification of Rocks.—A petrological basis of arrangement is easily found in the observed fact that all rocks which have been deposited as sediments on the bottoms of seas, lakes, and rivers are arranged in regular layers, beds, or *strata*. Those rocks, on the contrary, which have consolidated from a state of igneous fusion are always *unstratified* and massive in their structure. Hence we have a primary distinction into *Stratified* and *Unstratified* rocks, and it will also be found that most of the stratified rocks are fragmental (and derivative), while most of the unstratified rocks are crystalline.

Certain rocks will, however, be met with, which present a combination of these characters, possessing a more or less crystalline texture, and yet showing signs of having once been arranged in regular strata. Other rocks exhibit a peculiar fissile structure, which causes them to split along planes which are more or less oblique to the planes of bedding. It is natural, therefore, to conclude that such rocks have undergone a considerable amount of alteration since the period of their original formation, and that new structures have been superinduced upon that of stratification. This kind of alteration is called Metamorphism, and the rocks so affected are called *Metamorphic rocks*.

A petrological classification therefore, founded upon the structural differences of rocks, is a more natural and convenient system of arrangement than that based upon their textural and mineralogical composition. It suggests a twofold division into—1. Stratified rocks; 2. Unstratified rocks, each of these primary groups having a sub-group of Metamorphic rocks.

Historical Classification of Rocks.—A third method of classifying rocks may be deduced from general considerations on the history of their formation. On the supposition that this globe was once an incandescent mass, the earliest rocks would be those which formed its solidified crust. These we should expect would bear some resem-

blance to the streams of lava still ejected by volcanoes. As the rain fell, as the waters gathered upon the cooling mass. as the winds and waves and tides began to work, portions of this crust would be ground to powder, and some of the constituents would be dissolved in the waters. The pulverized material would be swept away and deposited in the calmer depths; the dissolved matter, under favourable circumstances, might here and there be precipitated. In process of time, moreover, when life had appeared on the globe, animals and plants would from this dissolved matter derive materials for building up the solid parts of their bodies, and after their death these would form the accumulations of organic origin already described.

From this point of view, therefore, all rocks appear to fall naturally into two great divisions according to the history of their formation; viz., those which are *Original*, or parts of the incandescent material of the earth, and those which are *Derivative*, or constructed of materials obtained from the former by various secondary processes.

Furthermore, it is obvious that in the lapse of time the structures and component minerals of the members of both these great divisions must be more or less changed by the influence of the various agencies to which they have been subjected; especially if in the course of their history they have been covered up by thick layers of superincumbent rock, and exposed while damp to a higher temperature and to a great pressure. These are the Altered or *Metamorphic* rocks already mentioned, and it is important to note that these rocks may once have belonged to either of the other great groups, *i.e.*, they may have been either Original or Derivative.

A comparison of the Petrological and Historical methods of classification will show that the two arrangements are parallel. The two primary rock-groups in each correspond exactly with one another, for all the Original or Igneous rocks are *unstratified*, and all the Derivative rocks are *stratified*. Both lines of thought also lead to the establishment of subdivisions to include the Metamorphic rocks, or those which are *altered* from their primary condition. From the coincidence of these results we may feel convinced that the most natural and appropriate classifi-

cation of rocks is into the following groups and sub-groups:—

Primary groups.	Sub-groups.
1. Original, Unstratified or Igneous Rocks.	*A.* Unaltered.
	B. Altered.
2. Derivative, Stratified or Aqueous Rocks.	*A.* Unaltered.
	B. Altered.

Under these names, therefore, they will be described in the following chapters.

1. **Igneous Rocks** strictly comprise only those which have consolidated and crystallized from a state of igneous fusion, and none of them present that regular kind of stratification which is characteristic of all rocks deposited in water. They occasionally occur in the form of sheets which are interbedded with truly stratified rocks, and thus simulate strata, but these are either the outspread terminations of very liquid lava-streams, or are intrusive sheets of molten lava which have been injected between two stratified beds.

Igneous rocks are, in fact, either parts of the deep-seated masses of molten material which lay beneath the roots of ancient volcanoes, and were intruded upwards into the rocks through which the volcanic orifices were opened, or they are portions of the lavas which were actually ejected through these orifices on to the surface of the earth. They are always, therefore, *intrusive* or else *eruptive* rocks.

2. **Derivative or Stratified Rocks** may be fragmental or crystalline; those which have been mechanically formed are all fragmental; those which have been chemically precipitated are generally crystalline, and those composed of organic remains are sometimes partially crystalline. These deposits are often called the Aqueous or Sedimentary rocks, but if we use these terms strictly we should exclude those accumulations which have been formed by the agency of the wind, and which are by some formed into a fourth class under the name of *Aerial* or *Eolian* rocks. These are, however, of comparatively small importance, and need not be excluded from this class if we adhere to the names of Stratified or Derivative rocks. In

the same class also should be placed those volcanic ejectamenta which sometimes fall on land and sometimes into the sea, and which are generally more or less stratified. These, however, are sometimes considered as belonging to the Igneous rocks, as resulting from volcanic explosions, though they have not cooled from a state of fusion. Mechanical deposits are therefore divisible into three sections: 1, Aqueous; 2, Eolian; 3, Volcanic.

Metamorphic Rocks.—Although these are naturally included under one or other of the primary rock-groups, yet it is often convenient to regard them as forming a distinct group, comprising all rocks which have been so altered in course of time, that either their structure or their mineral composition, or both, are different from that which they first possessed. The characters exhibited by some appear to have been mainly produced by the mechanical stress of vertical or lateral pressure; others have been affected by the chemical action of percolating waters and permeating gases at depths where these influences are assisted by that of heat; so that their ingredients have formed new combinations, and have re-arranged themselves in crystalline forms. All these causes have combined to produce a number of rocks which are more or less altered, and are therefore different from any of the deposits that are now being formed on or near the surface of the earth. The whole group falls naturally into two sections, viz., the Metamorphic igneous rocks, and the Metamorphic derivative rocks.

"It is often asserted that the process of metamorphism has sometimes been carried so far as to obliterate all trace of the original history of the rock; in other words, that rocks exist which, from their relations to other more intractable, and therefore less altered strata, appear to be of derivative origin, but which have become absolutely indistinguishable from members of the original or igneous group of rocks. This passing of rock from the condition indicative of metamorphism to that characteristic of its having solidified from a state of fusion is, in itself, quite conceivable, and undoubtedly there are cases where it is very hard to distinguish, in the present state of our knowledge, between an igneous and a metamorphic rock; but

it is certainly the case that the majority of instances brought forward in proof of this extreme metamorphism have broken down on careful examination, and that many of them have been supported by such slender evidence as to imply either great carelessness or great ignorance on the part of the observer." [1]

Determination of Rocks.—The petrological relations of rocks must be studied in the open country by examining the structure of the rock-masses which are exposed in pits, quarries, and cuttings of all kinds. It is in this way only that the facts of geology are obtained, and by such observations the student will easily learn to determine at once whether any given rock be Igneous, Stratified, or Metamorphic. Mr. Jukes has well remarked that "a blind man might just as well try to learn the art of painting, as any one attempt to understand geology without personal observation of those objects on the structure of which the whole science depends."

It would be useless, therefore, to burden the reader's memory with minute directions for distinguishing between hand specimens of the three great classes of rocks above mentioned; but the case is different when the necessity arises for distinguishing between the different members of any one class of rocks.

The naked eye or a hand-lens will generally inform us whether a rock be crystalline or not, and will give us some insight into the textural arrangement of its component particles; a knife will often guide us in ascertaining what minerals it is composed of by the degree of hardness and resistance they possess.

It is very unsafe, however, to trust in such rough and ready methods of determination, especially in the case of the igneous rocks, and English geologists were formerly often led astray by omitting to avail themselves of the more accurate means of determination. These other methods are microscopic and chemical analysis.

Microscopic Analysis.—It is now universally admitted that the microscope is of the greatest use in determining the mineral composition, texture, and probable method of

[1] From MS. notes by Prof. Bonney.

origin of all kinds of rocks, and that without its assistance it would be and has been impossible to arrive at a natural classification of the igneous rocks.

For the purpose of examining a rock under the microscope, a thin chip or slice of it is taken, ground smooth, and polished on one side. The polished surface is then cemented with Canada balsam on to a piece of plate glass, and the other side is ground down until the section is of the required thinness and transparency. The Canada balsam is then melted, and the slice is carefully pushed off into a dish of turpentine, in which it is washed, so as to remove all traces of the emery powder and other substances used in the grinding and polishing process. The preparation is then mounted on a glass slide with Canada balsam and overlaid with a thin glass cover, care being taken to remove all air-bubbles from inside.

The advantages accruing from the microscopical examination of such slices are especially great in the case of rocks whose texture is so fine and close that their mineral composition could not be ascertained by examination with ordinary hand-lenses.

As Dr. Geikie observes: "A rock-section prepared in this way enables us to ascertain with precision the manner in which the different minerals are built into each other, and often throws a flood of light on the origin of a rock, and on the subsequent changes which the rock has undergone. It furnishes an opportunity of applying the delicate analysis of polarized light, and thus reveals points of structure in the composition of a rock which could not be ascertained in any other way."[1]

For information regarding the methods of examining rock-slices under the microscope, the reader is referred to Geikie's "Textbook of Geology," p. 188, and Rutley's "Study of Rocks," p. 74.

Chemical Analysis.—Though in the case of crystalline and fragmental rocks, a microscopical examination will usually enable us to decide what minerals are present, yet it will not do so in the case of igneous rocks in a crypto-crystalline or

[1] "Manual of Geology," Jukes and Geikie, 1872, p. 95.

vitreous state; neither will it reveal the actual proportions of the different minerals or elements present in stratified rocks. It is only by chemical analysis that we can ascertain the ultimate chemical composition of such rocks, and the relative proportion of the different elements they contain. Such information will enable us to determine what minerals can or cannot be present, and what compounds they would form if they had crystallized out, or we may compare the analysis with that of allied crystalline varieties, the mineral constituents of which are already known.

CHAPTER III.

ORIGINAL OR IGNEOUS ROCKS.[1]

A. *Unaltered.*

AS these have solidified from a state of fusion by heat, their present appearance will obviously be the result of two causes: 1, their chemical constitution; 2, the circumstances of cooling. To the former is due the presence of certain minerals and the absence of others; on the latter depends the structural condition of the rock, whether it is a glass, or has assumed a more or less crystalline structure.

For these rocks, then, which from the circumstances of their formation are called Igneous, the most natural basis of classification would seem to be that of their mineral composition. Each division thus formed will be either composed of certain minerals, or will consist of materials which are capable of forming these minerals. A further subdivision can be made of each group according to the crystalline condition in which the rocks occur, that is, according as the component minerals are more or less perfectly defined, or as the rock still remains in the state of a glass.

In order to carry these principles of classification into effect, it is necessary to make use of microscopical as well as of chemical analysis.

Mineral Composition.—All the minerals which ordinarily enter into the composition of igneous rocks are silicates, and free silica in the form of quartz is also frequently present. The total percentage of silica which they possess is sometimes as high as 80, sometimes as low as 40, or a little less; hence these rocks are often simply divided into *acid* and *basic*, according as they contain more or less than 60 per cent. of this mineral.

The chief mineral components of igneous rocks have

[1] This chapter has been contributed by Prof. T. G. Bonney, F.R.S.

already been described, but it is seldom that many of these occur together in one rock, and certain laws or rules can be laid down regarding their *paragenesis* or association. We can easily understand that when the original molten mass contained a large percentage of silica, its crystallization would give rise to the formation of the more highly silicated felspars, and there might still be a surplus of silica which would remain as free quartz; while in a mass with a low percentage of silica, there might only be sufficient to form the less highly silicated felspars, without any surplus remaining. As a rule, therefore, free quartz is associated with the more highly silicated felspars, such Orthoclase, Albite, and Oligoclase; quartz may occur as an accessory mineral in company with Labradorite or Anorthite, but never as an important constituent of the rock.

Hornblende also is more commonly found in assocation with the highly silicated felspars, while Augite is generally associated with the more basic felspars, and with Leucite and Nepheline. Olivine, also, as might be expected, is always associated with the more basic felspars, and sometimes occurs alone with Augite and Enstatite. Hypersthene, a mineral less common than is usually supposed, has the same habit.[1]

The classification of igneous rocks adopted in the following pages is founded upon their mineralogical differences, or the association of different minerals in different rocks.

Structural Differences.—These afford the means of further subdivision, for we know, as a matter of experiment, that from the same materials, after fusion, may be obtained either a translucent glass or an opaque stone, built up more or less completely of crystalline particles, and by means of the microscope it is found that the matrix, or ground mass, of a rock may be in one of the following conditions:—

A. It may be a true glass (when it is often termed the base). In this case, when a thin slice of it is placed between the crossed nicol prisms of a microscope with a

[1] Recently, however, a mineral supposed to be hypersthene has been noted in association with some of the more highly silicated felspars.

polarizing apparatus, the field remains dark as the stage is rotated. Rocks with a glassy base are said to be *vitreous*.

B. If small, faint, and rather ill-defined patches of light, like the ghosts of crystals, appear and disappear as the stage is rotated, so that no part remains dark throughout a whole revolution, the ground mass is said to be *crypto-crystalline*.

C. If the patches are more definite in shape and rather larger in size, sometimes showing bright tints, so that it is possible to identify the different component minerals, the mass is said to be *micro-crystalline*. In this state, however, the crystalline grains are often a little indefinite at the boundaries, and do not commonly exhibit the outline of their normal form.

D. If the slide is a mass of well-defined crystals, clearly distinguishable one from another, of which those first solidified give indications of their normal external form, the rock is then said to be *crystalline*.

The second of these conditions is in many cases the result of *devitrification*, the gradual change from a vitreous to a semi-crystalline state which a glass undergoes if it is kept for a considerable time at the point of incipient softening. In such case a crypto-crystalline rock might fairly be regarded as metamorphosed; but seeing that we are not yet able to distinguish satisfactorily between cases where the structure is original and where it is secondary, the separation is not generally attempted. Neither is it easy at present to separate rocks with this structure from those of the micro-crystalline group, so that we shall speak of both inclusively as *semi-crystalline*.

Glassy and semi-crystalline varieties are of frequent occurrence among the acid rocks, but are rare and more limited in mass among the basic rocks, and in some instances have not yet received distinctive names.

Conspicuous isolated crystals of any one or more of the component minerals may occur in glassy, semi-crystalline, or crystalline rocks, giving what is termed a *porphyritic* structure. The name Porphyry was first applied to the dark red or purple rock, speckled with light-coloured felspar, obtained from Jebel Dokhan in Egypt, and largely used by the Romans for decorative purposes. By some

means the term became applied in process of time to rocks of the most diverse mineral composition, but exhibiting the same peculiarity of structure, viz., the conspicuous occurrence of one mineral in a more compact matrix. The adjective *porphyritic* is now always used with this meaning, which of course the etymology (*porphyra*, purple) does not sanction; but the name Porphyry should no longer be employed as the designation of any rock. In the case of the glassy, and perhaps also the semi-crystalline rocks, it is thought probable that these isolated crystals are the remains of a former state of solidification, and have survived the last melting down of the rock.

If the mass of a rock is full of small cavities or vesicles it is said to be *vesicular*; the cavities are generally elongated in one direction, and when they are subsequently filled up with some mineral such as quartz or calcite, the infiltration is called an *amygdaloid* (*amygdalon*, an almond), and the rock is said to be *amygdaloidal*.

Classification of Igneous Rocks.—It may perhaps assist the learner if we commence by fixing our attention upon the crystalline representatives of the various rocks, and regarding the less easily recognizable semi-crystalline and glassy varieties as included with them in a single group which we may afterwards subdivide. In ascertaining to which subdivision the above-mentioned varieties should be referred, we are guided by chemical analysis, and aided by the occurrence of minerals porphyritically developed. We shall also remember what has been said about the general habit of association (or paragenesis) of the felspar, and be prepared for various minor subsidiary and connecting groups. Grouping them by the dominant minerals and remembering always that more than one species of felspar may occur in a rock, and that hornblende or augite are often associated with or replaced by magnesia mica, we have the following rude classification:—

(A.) GRANITE GROUP.—Quartz + Orthoclase felspar + Mica.

(B.) TONALITE GROUP.—Quartz + Plagioclase felspar + Hornblende.

(C.) SYENITE GROUP.—Orthoclase felspar + Hornblende.

(D.) DIORITE GROUP.—Plagioclase felspar + Hornblende.

(E.) DOLERITE GROUP.— { Plagioclase / Nepheline / Leucite } + Augite.

(F.) PERIDOTITE GROUP.—Olivine + Augite (commonly + Enstatite).[1]

Partly as varietal forms and partly as connecting links of these groups we have the following:—

(C.[1]) MINETTE GROUP.—Orthoclase felspar + Mica (with some Hornblende or Augite).

(D.[2]) KERSANTITE GROUP.—Plagioclase felspar + Mica (with some Hornblende or Augite).

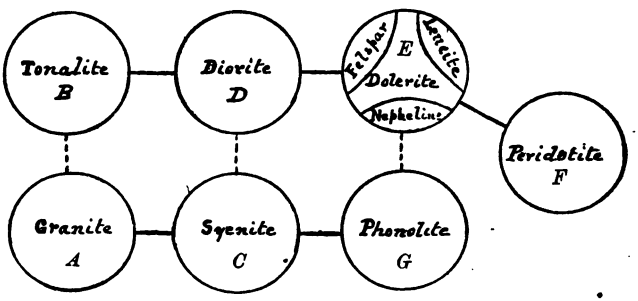

Fig. 60.

(G.) PHONOLITE GROUP.—Orthoclase felspar + Nepheline + Hornblende.

We also find that the very composite group, E, Dolerite, is capable of subdivision into three marked sub-groups according as the dominant mineral is a Plagioclase felspar (such as labradorite or anorthite), Nepheline, or Leucite; these are generally called the Felspar-dolerites, the Nepheline-dolerites, and the Leucite-dolerites—the last two being named by some authors Nephelenite and Leucitite respectively. Indeed, although connecting forms exist which some gather into a Tephrite group, these are generally so

[1] In all cases an iron oxide, magnetite, hematite, or ilmenite, is present as a constituent, which is usually most abundant in the more basic varieties.

distinct that we have been led to associate them rather because of the poverty of our nomenclature than of their exceptionally close relationship. It is also obvious from what we have said above, that we may expect connecting links between A and B, or C and D, by the gradual substitution of a soda for a potash felspar; and between A and C, or B and D, by the gradual disappearance of the free quartz. Further, as olivine is frequently present in E, especially in the better known and commoner Felspar-dolerite subdivision, we may expect to meet with forms connecting it with F (Peridotite group).

The annexed diagram, (Fig. 60) then, may represent the relationships of these groups in a graphic form.

Proceeding now to the fuller discussion of these groups, with their subdivisions dependent on crystalline conditions and with their minor varieties, we have the following :—

(A.) Granite Group.

(1.) *Crystalline.*—Quartz + orthoclase (and some plagioclase) + mica (either potash or magnesia mica) with or without hornblende—**Granite.**

Where the third constituent is almost absent the rock is called *Pegmatite;* where the quartz and felspar have a peculiar arrangement so that the former has a rude resemblance to a series of Hebrew characters, it is called *Graphic-granite;* where hornblende more or less replaces mica, it is called *Hornblendic-granite;*[1] when there is much plagioclase, *Miarolite.* A fine grained variety, poor in mica, is called *Aplite.*

(2.) *Semi-crystalline.*—The same minerals occurring porphyritically (but commonly with less mica)—**Quartz-felsite.**

This rock is very commonly called *Quartz-porphyry;* but to this name there is an objection that the term Porphyry has been applied to so many rocks essentially different in their mineral constitution. The rock is also called *Elvanite,* from a Cornish word *Elvan;* a very bad term, because the rock is abundant in many other districts, and even in Cornwall

[1] The Syenite of some authors.

only the "buff elvans" are representatives of this particular rock.

(3.) *Glassy.*—The same minerals (or augite) occurring sometimes porphyritically—**Quartz-trachyte.** This rock is also called Liparite and Rhyolite. It may, perhaps, be found convenient to restrict the latter of these names to the more compact varieties, which often give indications of a fluidal structure. Well-marked varieties are **Obsidian** and **Pitchstone.** These differ from *Quartz-trachyte* in having a more distinctly glassy aspect, which seems due to the fact that the latter is generally crowded with microliths, and sometimes assumes a crypto-crystalline structure. These two rocks differ from one another thus: *Obsidian* has a very conchoidal fracture and a glassy lustre (being very like dark glass); *Pitchstone* has a more splintery fracture and a resinous lustre. It is not easy to say to what this fairly persistent difference is due.

(B.) Tonalite Group.

(1.) *Crystalline.*—Quartz + plagioclase (generally oligoclase) + hornblende. Magnesia mica is not seldom present, and sometimes is abundant. A very large mass of this rock occurs in the Adamello group near the Tonale Pass, whence the name. By many authors, however, the rock is simply called **Quartz-diorite.**

(2.) *Semi-crystalline.*—The same minerals occurring porphyritically, but commonly the hornblendic or micaceous element less abundant—**Quartz-porphyrite.**

(3.) *Glassy.*—The same minerals (or augite), occurring sometimes porphyritically. This rock is called **Dacite,** from the ancient Dacia, in which district it occurs. It is also called *Quartz-Andesite,* from the Andes, where it is also found. These rocks are analogous to the quartz-trachyte of the former group. There are also very glassy forms, but these as a rule can only be distinguished by chemical analysis from Obsidian and Pitchstone, and have not yet received distinctive names.

(C.) Syenite Group.

(1.) *Crystalline.*—Orthoclase + hornblende. Plagioclase felspar usually, and mica often present.[1] Augite is also said occasionally to replace hornblende—**Syenite.**

(2.) *Semi-crystalline.*—The same minerals present porphyritically—*Orthoclase-felsite* or **Felsite.**

(3.) *Glassy.*—Same minerals present porphyritically; felspar usually sanidine—**Sanidine-trachyte.** Some of the *Obsidians* and *Pitchstones* may more properly belong to this group.

(C.[1]) Minette Group.

This forms a portion of the rather limited series of rocks often distinguished as *Mica-traps.*[2] Mica (more commonly magnesia-mica) is always a conspicuous constituent. Some free quartz is occasionally present, and more or less hornblende or augite. The nomenclature of the group is imperfect. It will probably be found convenient to restrict the term **Minette** to the crystalline form, and designate the others respectively *Minette-felsite* or *Mica-felsite*, and *Minette-trachyte* or *Mica-trachyte.*

(D.) Diorite Group.

The three divisions of this group, **Diorite, Porphyrite,** and **Andesite,**[3] differ only from those of B, into which they graduate, in the absence of free quartz. The felspar is generally oligoclase (or albite), but sometimes labradorite or anorthite; but inasmuch as hornblende is known to be sometimes found as a secondary product after augite, it is difficult to say how far it is to be regarded in these cases as a primary constituent. The anorthite-hornblende rocks (crystalline) are often distinguished as **Corsite**; and a very peculiar and beautiful form in which the felspar and horn-

[1] When this is conspicuous, the rock is sometimes called *Mica-syenite.*

[2] The *mica-traps* commonly occur in dykes, veins, and small intrusive masses; and, so far as at present known, are precarboniferous in age.

[3] Some authors make a *Propylite* group (quartziferous and quartz-less) distinct from the *Andesites;* the writer is not convinced that the members of this are anything else but older *Andesites.*

blende form globular masses an inch or more in diameter, with a zonal arrangement of the two minerals, found at one locality in the island of Corsica, is called *Napoleonite*.

(D.[1]) Kersantite Group.

This contains the remainder of the Mica-trap group, which differs from the Minette group as above described in that a plagioclastic felspar replaces the orthoclase. There is at present the same deficiency in the nomenclature, the term Kersantite being applied to the crystalline or more conspicuous representatives.

(E.) Dolerite Group.

(*a.*) *Felspar sub-group.*—The nomenclature of this group, though five members are common, is at present not very precise. The type-rock may be defined as consisting of a plagioclastic felspar, generally labradorite, and of augite, with more or less iron peroxide, and commonly some olivine.[1] Magnesia mica is often present, and sometimes rather abundant. When the two principal constituents are visible to the unaided eye, forming a speckled whitish and black rock, it is called **Dolerite**, and when the constituents are so minute that the rock is black, it is called **Basalt**.[2] No name is thus applied to the (rare) semi-crystalline variety; the glassy form, also rare and limited in thickness (it not seldom exists as a mere coating to ordinary basalt masses), is called **Tachylite**. This is a black or brownish-black glass distinguishable from obsidian chiefly by its greater specific gravity and easier fusibility with the blowpipe. **Gabbro** is a rock closely related to dolerite; it is coarsely crystalline, always in masses, and apparently a deep-seated rock; the pyroxenic constituent is partially or wholly in the form of diallage. Occasionally, while olivine is abundant, the pyroxenic constituent is comparatively wanting.

[1] As this mineral is frequently abundant enough to become an important constituent, while in other cases it is entirely absent, some have proposed to restrict the term *dolerite* to the former; the writer does not think that the distinction can be maintained.

[2] The term *Anamesite* has been applied to intermediate varieties.

(*b.*) *Nepheline-Dolerite* (or *Nephelenite*).—The rocks of this differ from the last in containing nepheline instead of felspar; there is the same want of preciseness in the nomenclature. The coarser varieties are easily recognized; the finer require microscopic examination. The rock, however, is commonly a little lighter in colour than a felspar basalt.

(*c.*) *Leucite-Dolerite* (or *Leucitite*).—The rocks of this differ from the felspar-basalts in containing leucite instead of felspar. The rock, as a rule, is decidedly lighter in colour than the others, and the augite is sometimes green.

Intermediate forms, containing two or all of the three minerals felspar, nepheline, and leucite, occur, and the more marked varieties (sometimes placed in a separate subgroup) are called *Tephrites*.

(F.) Peridotite Group.

The nomenclature of this rather rare group is also in need of revision. The great majority of its members are crystalline, and the rock appears to be generally a deep-seated one. Olivine is the essential constituent, and with it enstatite or augite, or both together, are commonly associated. There is always some iron peroxide, and small quantities of chrome and nickel are generally detected by analysis. *Lherzolite*[1] is the name given to a species consisting of olivine, enstatite, augite (the variety diopside) and picotite (a variety of spinel). *Dunite*[2] appears to be chiefly olivine and chromic iron. *Eulysite* contains garnets and black mica. *Limburgite* is a glassy form with porphyritic crystals of olivine and augite. *Picrite* contains olivine, augite (or hornblende), with usually some mica and often a little felspar. In *Picrite* the pyroxenic constituent generally rather predominates over the peridotic, and the rock appears to be rather an ancient one.

[1] From Lake Lherz in the Pyrenees (Ariège), where the rock occurs.
[2] From the Dun Mountain, New Zealand.

(G.) Phonolite Group.

There remains this outlying group (which, except for the prominence generally given to it, we should have treated as a sub-group). On the whole it may be regarded as most nearly connected with the syenites. The normal rock may be defined as consisting of orthoclase (especially sanidine), nepheline, and hornblende; but plagioclase felspar, leucite, hauyne, and mica often occur as accessories, or even in sufficient abundance as to constitute well marked varieties; augite also may occur. The group of rocks commonly designated phonolites is generally not earlier than of tertiary age, and the semi-crystalline and glassy varieties have not received names, but older representatives are known in the coarsely crystalline *Elæolite-syenites*, which consist normally of orthoclase, elæolite (a massive variety of nepheline), and hornblende, in which zircon is often present, together with *Foyaite*[1] (containing also sodalite), and one or two other allied varieties. A porphyrite found in the *Fassathal* (South Tyrol), perhaps of secondary age, contains Liebenerite, which is an altered form of nepheline. The group obviously approaches, on one side, the Tephrites, and so draws near to the Nepheline-dolerites.

[Many authors make a Garnet group, but in the present state of our information we prefer simply to mention these rocks. Garnet is occasionally present in igneous rocks, and not seldom appears to be an original constituent: it is also very common in metamorphic rocks, and is frequent in both igneous and sedimentary rocks near the junction of the two. The most remarkable members of the group are the *Eclogites:* rocks consisting mainly of red garnets and hornblende (commonly the bright green variety). They are not common, and the information concerning them is remarkably hazy and contradictory. Perhaps on further examination it will be found that some of them are exceptional varieties of an igneous rock related to the *Diorites*, and others are of sedimentary origin related to the hornblende schists, described below.]

[1] From the Foya Mountains (Portugal).

It was formerly customary to subdivide the igneous rocks into three groups, according to the circumstances under which they were presumed to have solidified. These were, respectively, VOLCANIC, or those which had cooled down in the open air; TRAPPEAN, or those which had solidified under comparatively slight pressure, as on the bed of the ocean; and PLUTONIC, or those which had solidified deep within the earth. The name given to the second group was from a Swedish word *trappa*, a stair, because the ends of the tabular rock-masses referred to this division had often a step-like aspect. More careful investigation, however, showed that many of the more typical members of this division had solidified in the open air, and that it was impossible to fix on any set of characters which separated them from the ordinary volcanic rocks or lavas, as they are often called. It then became usual to divide the igneous rocks simply into VOLCANIC and PLUTONIC, but here it at once became difficult, owing to the more ready crystallization of the basic kinds, to know where to draw the line. Hence these terms have been abandoned for purposes of precise classification, and are only used as general inclusive names of no very definite meaning, which, however, are often useful. In the same way the word *trap* is still retained, to designate any rather compact igneous rock, of not very modern origin, occurring normally in tabular masses. It is what we may call a traveller's term, one used legitimately when a more precise one is impossible.

Felstone and *Greenstone* designate a large group of rocks (most of which would anciently have been included in the Traps) which are too compact in their structure to allow their crystalline condition and mineral constitution to be readily distinguished,—*felstone* including the felsites, porphyrites, and, perhaps accidentally, some phonolites, and *greenstone* the more compact diorites, diabases, and slightly decomposed basalts. The intermediate term *Greystone* has been occasionally used for some of the darker felsites, the phonolites, and some of the paler basalts. *Aphanite* has been used for the more compact diorites, but as it is impossible to distinguish very fine-grained hornblendic and augitic rocks without the microscope, the term seems to be needless if used in an exact sense, and if otherwise to have

no advantage over "compact greenstone." Melaphyre is another vague term of dubious advantage. It has been applied to dark compact rocks of considerable geologic age, defined as normally consisting of "felspar (plagioclase), augite, and iron peroxide." Further examination has shown that some of these rocks are *porphyrites*, but the majority simply rather ancient *basalts*, and so far as the term bears any precise meaning it is equivalent to "probably basalt, certainly old." It has, however, been used so vaguely, though with an air of exactness, that perhaps it is better not to employ it. *Porphyry*, again, is a term for the same reason objectionable. The term *Porphyrite*, applied to a group of felstones which are very commonly of a more or less purplish colour, and to which the original porphyry belonged, is legitimately retained, but in the writer's opinion it would be better to discard *porphyry* altogether as a term of classificatory value. Invariable use, notwithstanding etymology, may be regarded as sanctioning the use of *porphyritic*. *Amygdaloid* is a term sometimes used as if it designated a species of rock. Obviously this is not the case; as, however, the more basic rocks are more generally amygdaloidal, the speaker commonly means an amygdaloidal basalt.

Metamorphic Igneous Rocks.

Granite Group.

Tourmaline Granites.—In granites the mica and felspar are sometimes, more or less, replaced by tourmaline; the result of secondary action in the more marked, if not in all cases. A beautiful variety of such granite, where crystals of red orthoclase are scattered through a matrix of quartz and schorl (black tourmaline) is found at Luxullian, in Cornwall, and is called *Luxullianite*. A granular mixture of quartz and schorl, without felspar, is termed *Schorl-Rock*.

Zwitter and Greissen.—Sometimes chlorite, cassiterite (tin-ore), or arsenical pyrites are added to the ordinary constituents of granite, forming a blackish rock which

is called Zwitter-rock. If the felspar has to a great extent disappeared, and the mica is Lepidolite (Lithia Mica), the rock is called Greissen.

Claystone is a more or less decomposed form of Felstone. Some of the old glassy rocks have become devitrified, and so properly belong to the Metamorphic series; but, as already mentioned, it is difficult to separate them, and no separate names have yet been assigned to these altered forms.

Dolerite Group.

No very conspicuous representatives exist of the intervening groups, but of this there are several.

Euphotides.—In gabbro the felspar has often been converted into a hard white mineral allied to saussurite, and the diallage into hornblende (in some cases the pretty green variety called Smaragdite). The rock thus altered is called *Euphotide, Hornblendic,* or *Smaragdite-gabbro.* A variety where the felspar appears to be anorthite, the pyroxenic constituent is rather rare, and the abundant olivine is more or less converted into serpentine, is called *Troktolite* or *Forellen-stein.*

Diabase.—Similar, though less definite changes have converted dolerites and basalts into Diabase, by the development of a chloritic mineral, commonly with a little calcite. If the augite is converted into uralite, the rock is termed *Uralite-diabase.*[1]

Basalt sometimes becomes so much decomposed, that water and carbonic acid constitute about a fifth part of the rock, and the alkalies are almost lost: the rock assuming an earthy texture and a pale cream-coloured tint. This is called *White-trap,* and is far from rare among the carboniferous rocks of Staffordshire and central Scotland.

Peridotite Group.

Serpentine.—This term has been used with great vagueness, and has been applied to a large group of rocks of various origins which have absolutely nothing in com-

[1] Hornblende does sometimes appear to be an accessory mineral in true gabbro or dolerite.

mon except the presence of a fair proportion of silicates of magnesia. Properly, however, the term should be restricted to the well-defined group of rocks, of which the Serpentine of the Lizard, in Cornwall, is an excellent type—a compact massive rock, of various dull brown, red, and green tints, in which glittering crystals of a certain variety of enstatite are frequently conspicuous. It may be considered as proved, that these rocks are altered Peridotites; chemically, they are mainly composed of silicate of magnesia, with iron oxides, and about 12 per cent. of water.

Conditions of Temperature and Pressure under which Igneous Rocks were formed.—In an important paper on "The Microscopical Structure of Crystals,"[1] Mr. H. C. Sorby has shown that it is possible to arrive at some interesting and remarkable conclusions as to the temperature and pressure under which the crystalline particles of granite and other igneous rocks were formed. The following is an abstract of his argument:—

When artificial crystals are examined with the microscope, it is seen that they have often caught up and enclosed within their solid substance portions of the material surrounding them at the same time when they are being formed. Thus, if they are produced by sublimation, small portions of air or vapour are caught up, so as to form apparently empty cavities; or if they are deposited from solution in water, small quantities of water are enclosed, so as to form fluid-cavities. In a similar manner, if crystals are formed from a state of igneous fusion, crystallizing out from a fused-stone solvent, portions of this fused stone became entangled, which, on cooling, remain in a glassy condition, or become stony, so as to produce what may be called glass- or stone-cavities. All these kinds of cavities can readily be seen with suitable magnifying powers, and distinguished from each other by various definite peculiarities.

From these and other facts the following conclusions are deduced:—

1. Crystals containing only cavities with water were formed from solution.

[1] "Quart. Journ. Geol. Soc." vol. xiv. p. 453.

2. Crystals containing only stone- or glass-cavities were formed from a state of igneous fusion.

3. Crystals containing both water- and stone- or glass-cavities were formed under great pressure by the combined influence of highly heated water and melted rock.

4. That the amount of water present in the cavities may, in some cases, be employed to deduce the temperature at which the crystals were formed.

Applying these principles to the examination of igneous rocks, Mr. Sorby proves from them the igneous origin of all, with this remarkable result, that the fluidity of the more superficial lavas was a more purely igneous one than that of the deeper seated trappean and plutonic rocks. The minerals of erupted lavas contain stone and glass cavities like the crystals formed in the slags of furnaces; but the blocks ejected from volcanoes contain water-cavities as well, the amount of water indicating that they were formed under great pressure and at a dull red heat, when both liquid water and melted rock were present. The crystals of the Cornish elvans and the Cornish and Scotch granites contain both fluid and stone cavities, proving the presence of water, and perhaps also of gas, as well as the conditions of great heat and pressure.

"On the whole, then," says Mr. Sorby, "the microscopical structure of the constituent minerals of granite is in every respect analogous to that of those formed at great depths and ejected from modern volcanoes, or that of the quartz in the trachyte of Ponza, as though granite had been formed under similar physical conditions, combining at once both igneous fusion, aqueous solution, and gaseous sublimation. The proof of the operation of water is quite as strong as that of heat."

Mr. Sorby arrives at the conclusion, that if granite and elvan finally consolidated at a temperature not exceeding 680° F., the elvans of Cornwall must have been formed under a pressure equal to that which would have been exerted by a thickness of about 40,000 feet of rock, those of the Highlands of Scotland one of 69,000, that of the granites of Cornwall indicate a pressure of about 50,000 feet, and those of the Highlands indicate one of 76,000 feet.

If the temperature of consolidation was higher, the pressure must have been greater. Mr. Sorby does not mean in his conclusions to point out the absolute depths at which the rocks consolidated, since the pressure they were subjected to might arise in part from the impelling force acting from below against the superincumbent mass.

CHAPTER IV.

DERIVATIVE OR STRATIFIED ROCKS.

THEIR Origin and Composition.—In Chapter III. we have examined the igneous rocks which come from the interior of the earth, and we have seen that they are essentially siliceous, some of them, especially the granites, containing crystals of pure silica, and all of them containing silicate of alumina. Now pure sand consists of grains of quartz, and pure clay consists of silicate of alumina combined with water. It is obvious, therefore, that clay and sand may be formed by the detrition and destruction of an igneous rock, such as granite, and this process may be actually watched wherever granite rocks are exposed to the erosive action of water.

All the sandy (arenaceous) and all the clayey (argillaceous) deposits, therefore, which are met with in the earth's crust, have been derived from some previously existing rocks, and these older rocks must either have been igneous rocks, or must originally have been derived from some igneous rock.

Similarly the siliceous and calcareous rocks of organic origin have been formed out of the silica and carbonate of lime held in solution by the sea-water; these materials having been primarily derived from the decomposition of the soluble silicates contained in igneous rocks.

The varieties of rock produced by the intermixture of the aluminous, quartzose, and calcareous elements are very numerous. The proportions of these ingredients in any deposit will depend partly on the character of the rocks exposed to erosion in the area whence the chief supply is derived, and partly on the amount of matter contributed by organisms to the sediment which is accumulating below. Thus the chemical composition of any stratified rock is

generally very variable: sands and sandstones frequently contain fragments of other minerals besides quartz; clay almost always contains a certain amount of lime and iron; and many limestones are rendered impure by an admixture of clay or siliceous matter.

Classification and Description.—As already stated, the whole group is naturally divided into two series—A, the unaltered rocks; B, the altered or metamorphic rocks. In dealing with the unaltered series it will be convenient to describe them under three heads, as below:—

1. Mechanically-formed.
2. Chemically-formed.
3. Organically-formed.

A. Unaltered Rocks.

1. *Mechanically-formed Rocks.*

We have already pointed out that the rocks included in this group are not all of subaqueous formation. Even rocks of similar aspect may have been formed by the operation of very different agencies; thus the materials of a sandstone may have been collected by currents of water, or they may have been accumulated by the action of wind; the materials of a breccia may have been gathered by the action of frost, or have been ejected from the crater of a volcano.

Conglomerate is a mass of consolidated gravel or shingle, the pebbles being rounded and waterworn, and set in some kind of matrix which binds them together into a firm rock. The pebbles may consist of any kind of hard rock or mineral which is capable of resisting continued attrition; and siliceous substances, from their great durability, are naturally the commonest constituents. When the rock consists chiefly of quartz pebbles it is called a Quartzose-conglomerate; when the pebbles are limestone, it is a Limestone-conglomerate, and so on. The matrix enclosing the pebbles also varies in composition; sometimes it is only sand, and the rock appears to have been consolidated simply by pressure, so that the pebbles may be removed

by a slight blow; in other cases the matrix consists of an infiltrated cement, either calcareous, ferruginous, or siliceous, and is sometimes so hard that a blow produces a direct fracture through matrix and pebbles alike.

Breccia is a mass of *angular* fragments cemented together in a similar manner. The agencies by which ordinary breccias are formed have been described on p. 144; but Prof. Bonney[1] has recently called attention to another class of breccias, which might be mistaken for the former, but have really been formed in a very different manner. These he terms "*crush breccias*," and believes them to have resulted from pressure or strain acting on a rock generally uniform, but containing weaker beds or portions, which have been crushed in situ into fragments of all shapes and sizes. They occur principally in the older rocks, and when the fragments are re-cemented by infiltrated matter they closely resemble an ordinary breccia.

Sandstone is consolidated sand, and the particles are usually quartz. They vary greatly as regards their degree of consolidation, from a mere *sand-rock* which is just compact enough to stand with a vertical face, to a hard and compact *gritstone*, which is capable of being used as a millstone. The size of the grains also varies from the minutest particles of quartz to grains as large as peas, the rock then commencing to pass into a conglomerate. There are many varieties of sandstone produced by the admixture of other mineral substances with the quartz grains.

Micaceous sandstone contains flakes of mica which are sometimes so abundant as to cause the rock to split into plates and slabs with glittering surfaces.

Felspathic sandstone contains grains of felspar, distinguishable by their dull white, yellow, or reddish colour, and peculiar fracture, imparting an earthy appearance to the rock.

Calcareous sandstones.—These are of two kinds: (1) An intimate mixture of fine sand and carbonate of lime, deposited contemporaneously; this, when very siliceous, is called *Firestone*, and when calcareous matter preponderates is called *Cornstone*, which often passes into an impure lime-

[1] "Geol. Mag.," Dec. 2, Vol. x. p. 435.

stone. (2) A sandstone in which the grains are bound together by a cement of carbonate of lime is called a *Calciferous sandstone.*

Argillaceous sandstones, or consolidated silts, are always fine-grained, and generally more or less laminated, so as to split easily along the planes of bedding; they are then called *Flagstones*, and may also contain a proportion of felspathic or micaceous material. There are other fine-grained rocks more or less argillaceous, but not markedly fissile, and for these the name of *Mudstone* will be found appropriate.

Glauconitic sandstone is a mixture of quartz and glauconite grains, generally with more or less carbonate of lime. It is usually called *Greensand.*

Sandstones with a siliceous matrix. — No special name has yet been given to these, but perhaps the French term *Psammite* might be used with this meaning. *Galliard* is locally used for such fine-grained siliceous grits, which break with a splintery fracture.

Some of the sandstones associated with shallow water deposits are doubtless ancient blown sands formed on terrestrial surfaces, and subsequently covered by strata of aqueous origin. In their general appearance they resemble the aqueously-formed sandstones, but when examined under the microscope, the grains of which they are composed are seen to be all more or less worn and rounded by attrition.

In the case of sand deposited in water the particles are buoyed up in the liquid, their relative weight being less and their friction on the bottom and against one another being proportionately diminished; under such circumstances a great amount of drifting and mechanical action must be required to wear down any quartz fragments into round grains. As a matter of fact, Mr. Sorby finds that the sand brought down by rivers is often very little worn, and that in marine sands the proportion of well-worn grains does not often exceed one-half.

But when drifted and worn by the wind in the open air the amount of friction is necessarily very much greater, and in sands so accumulated all the grains show signs of attrition, most of them being completely rounded, with a

surface which, under the microscope, looks like that of fine ground glass.

Clay.—Perfectly pure clay is a hydrated silicate of alumina, but the material ordinarily known as clay is a consolidated mud which contains sufficient silicate of alumina to be plastic or capable of retaining its shape when pressed or moulded. Common clay generally contains a certain amount of fine sand and calcareous matter, and is largely coloured by oxide or carbonate of iron.

Kaolin, or porcelain clay, is nearly pure clay, white and free from iron; its derivation from the decomposition of granite has been described on p. 72. *Pipe-clay* is a similar white clay, but liable to shrink when heated, and consequently not fit for making china. *Pottery clays* are less pure, and are always coloured with iron.

Siliceous clays.—Fire-clay contains a considerable quantity, often 50 or 60 per cent., of pure sand mixed with the silicate of alumina, and a good fire-clay must be free from lime, alkalies, and iron, which act as fluxes; it will then stand a very intense heat without melting. *Fullers' earth* is a soft greenish or bluish clay, containing about 50 per cent. of silica, 20 per cent. of alumina, 25 per cent. of water, and a little oxide of iron. *Loam* and *silt* are unconsolidated mixtures of clay and sand.

Calcareous clay or marl contains a variable proportion of carbonate of lime, if laminated it is sometimes called *marl-slate*.

Shale is the general term for a laminated clay, often called *Bind* or *Blue-bind* by miners and quarrymen; by colliers a carbonaceous shale is called *Batt*. The bituminous shales used for the manufacture of paraffin are known as *oil-shales*.

Boulder clay is a clayey deposit, full of stones and boulders, generally unstratified, and due to the agency of ice.

Loess, an earthy calcareous loam, resembling alluvial mud, but probably of terrestrial origin. Richthofen considers it to be the product of dust-storms such as are frequent in those treeless plains that are known as *steppes* in Russia and Central Asia, and as *prairies* in North America.

Agglomerate.—This rock bears the same relation to the volcanic sands and ashes as Conglomerate does to Sandstone. It consists of a confused assemblage of angular blocks embedded in a paste of finer materials, and is only found in close proximity to the volcano from which all the fragments have been ejected. The blocks are chiefly pieces of lava, but mingled with these are frequently fragments of the local stratified rocks, which have been rent by the outburst of the volcano. A volcanic agglomerate is a terrestrial rock, but if the same materials are ejected into lakes or seas, so that the blocks are more or less rounded and water-worn, a volcanic conglomerate is produced.

Volcanic Ash, Tuff, or Peperino, are names applied to the finer kinds of volcanic detritus; the sand, dust, and powder which is carried to a greater distance from the volcano. They are generally more or less regularly stratified, whether the deposits have been formed on land or on sea-bottoms, but in the latter case the volcanic ashes are mingled with the materials of ordinary stratified deposits, and sometimes contain organic remains.

Tuffs may be subdivided into two classes according to the felspathic or pyroxenic nature of the base or ground mass of the rock. The former are called Felstone Tuffs, tha latter Greenstone Tuffs.

Felstone Tuff varies in colour from white or grey to yellowish-red or dark brown; in texture it is generally earthy and flaky, and frequently contains broken crystals of felspar, or small fragments of some trachytic rock. Sometimes sand is mingled with this base, and the rock passes into a felspathic sandstone. A nodular concretionary structure is occasionally developed, the size of the nodules varying from that of nuts to that of cannon-balls. The more compact and indurated varieties are not easy to distinguish from felspathic lavas, until the aid of the microscope is called in; this is the case with some of the felspathic ashes or felstone tuffs of North Wales and the Lake district.

Greenstone tuff is usually dull and earthy in texture, with a prevailing dirty-green or purplish colour. Coarser gravelly varieties also exist which pass gradually into

volcanic agglomerate. In the central valley of Scotland there is a vast quantity of such tuff interstratified with the ordinary sedimentary rocks; Dr. A. Geikie describes it as made up of a paste of abraded dolerite rocks with fragments of these rocks and of shale, sandstone, limestone, &c. It has a prevalent green colour and is usually well stratified, but a nodular or cannon-ball structure is not uncommon. Similar greenstone tuffs occur in County Limerick, Ireland, and some of these contain fragments of vesicular greenstone (? Dolerite) such as is not known anywhere in the neighbourhood: these fragments are probably portions of the upper scoriaceous surface of the lava which was then rising in the ancient volcano from which the tuffs were ejected (Jukes).

Laterite is a rock of a brick-red colour, generally occurring in the form of layers between sheets of basalt. It is composed mainly of silicate of alumina and oxide of iron, and is probably in most cases a soil or rainwash derived from the decomposition of such lava currents.

2. *Organically-formed Rocks.*

Most of these rocks consist of mineral matter which has once been in a state of aqueous solution, but has been abstracted and secreted by the agency of various organisms for the construction of their hard parts. The constituent particles of these rocks therefore are principally fragments of the shells and skeletons of organic bodies, but the interstices between these particles are generally filled up with a contemporaneous deposit of fine calcareous mud, or by a subsequent infiltration of calcareous, or siliceous matter. Most organically formed rocks are then wholly calcareous, or wholly or partially siliceous. Coal is, of course, an exception, and has had an entirely different origin.

Limestone may be defined as a rock consisting principally of carbonate of lime, but all those limestones which have been accumulated as sediments of organic origin contain mechanical admixtures of alumina, silica, and iron, and very often enclose also chemically-formed nodules of the two latter substances. Like all other rocks limestones exhibit various degrees of consolidation, some are com-

pacted by pressure, others by the infiltration of a crystalline cement, and, in some cases, the whole rock has assumed a crystalline structure, which completely obscures its organic origin. The varieties of limestone are consequently very numerous, and their differences appear to depend upon the three following circumstances:—

1. The nature of the organic particles, whether derived from Corals, Mollusca, Crustacea, Echinoderms, or Foraminifera.
2. The proportion of other mineral matter mingled with these.
3. The extent of subsequent consolidation by pressure, infiltration, and crystallization.

The following are some of the more important and common varieties of limestone.

Chalk is a white, earthy, fine-grained limestone, sometimes soft and friable, sometimes hard and compact. Chemical analysis shows that it is very pure, the whiter varieties containing from 96 to 98 per cent. of carbonate of lime (see p. 230). Microscopical analysis shows that it consists partly of the minute shells of Foraminifera, partly of the broken fragments of the shells of bivalve Mollusca, the fibrous shells of a particular genus called *Inoceramus* furnishing the greater number of these fragments. Mr. Sorby finds that in most specimens of chalk which he has examined these shell-fragments are quite equal in bulk to that of the Foraminiferal remains, and in weight would far exceed the latter.

Oolite, or Roe-stone, consists of a number of small, round particles about the size of the eggs in the roe of a cod-fish. These little grains consist of carbonate of lime arranged in successive concentric coats round some minute particle of foreign matter which forms a nucleus. This nucleus may be a particle of sand, or a minute fragment of coral or any such substance. Some oolites simply consist of these spheroidal grains and are compacted by pressure; in others the interstices are filled up by fine-grained, calcareous mud; others are cemented by an infiltration of crystalline calcite. They usually form freestones, or rocks which can be cut with equal facility in any direction; Bath-stone

is a familiar example. The occurrence of oolitic rock in recent coral-reefs has been mentioned on p. 219. *Pisolite* is a variety in which the grains are as large as peas.

Shell limestone is a rock in which the shell-fragments are large and conspicuous, so that the nature of the organic remains is easily ascertained. Occasionally some particular fossil is so abundant as to give its name to the rock, thus we have *Nummulite limestone* from the large Foraminifera called *Nummulites;* and *Crinoidal limestone*, which is entirely composed of broken fragments of the Echinoderms called *Crinoids* or *Encrinites*.

Siliceous limestones contain, as their name implies, a certain amount of silica diffused through the calcareous mud. They are always fine-grained and hard, breaking with a splintery or conchoidal fracture. Limestones which contain a certain amount of silica and alumina afford the materials of hydraulic cement, and are called *Hydraulic limestones*. According to Gmelin, hydraulic cement is a pasty admixture of lime, silica, and water, which when immersed in water is gradually converted into a hydrated silicate of lime. When the silica is in the larger proportion the stone is called a *Chert* or *Cherty limestone*. It usually occurs in nodules, or thin beds, among other limestones, but sometimes forms a thick rock-mass. Mr. A. Strahan describes a mass of chert in Flintshire, over 300 feet in thickness and passing laterally into a granular sandstone compacted by siliceous cement, and ultimately into a conglomerate. *Cornstone* is a similar form of siliceous limestone, containing less silica.

Argillaceous limestone contains a variable admixture of clayey matter. When soft and unconsolidated it is known as *Marl*, when tolerably firm and compact it may be called a *Marly limestone;* and some varieties of hydraulic limestone would come under this denomination. *Clunch* is a common name for a tough, sandy marl.

Ferruginous limestone is a mixture of carbonate of lime with more or less carbonate of iron, and when the latter is in large proportion the rock is often termed an *Ironstone*, and is smelted for iron. The *marlstone rock-bed* of the Cleveland district is a rock of this kind; average specimens containing from 60 to 70 per cent. of carbonate of iron.

The action of percolating water has always oxidized more or less of the iron-carbonate, and the oxides thus formed stain the rock outside of a rusty-brown colour, while inside it is of a dull blue-grey. *Rottenstone* is a siliceous and ferruginous limestone from which the calcareous matter has been removed in solution and the iron oxidized, so that it is reduced to a mass of crumbling rotten-stone.

Magnesian limestone is a mixture of the carbonates of lime and magnesia, but as this is either a chemically-formed rock, or has resulted from the subsequent alteration of a limestone by chemical processes, we defer its description for the present.

Bituminous limestone is a black rock containing much carbonaceous matter derived from the decay of animal or vegetable matter. Many dark limestones emit a fetid smell when struck by a hammer, probably from the presence of animal matter, and the smell is sometimes so strong that the quarries can be smelt at a distance of a hundred yards. To such fetid limestones the Germans give the name of *stinkstein*.

Glauconite marl or *limestone* is one containing numerous grains of the mineral called Glauconite. When loose and unconsolidated the material is often called *Greensand* from the prevailing colour. Sandy particles are often present, but such *Greensands* are always more or less calcareous, and are more correctly termed *Marnes glauconifères* by the French. *Bargate Stone* and *Kentish Rag* are glauconite limestones.

Tripoli, or Polishing Slate, is an accumulation of the siliceous cells or frustules of the microscopic plants known as Diatoms. It is seldom that rocks are found so entirely composed of these organisms as that at Bilin, in Bohemia, whence Tripoli is obtained (see p. 182), but they have probably furnished the silica which is embodied in many siliceous limestones; and their remains have actually been detected in some American *Cornstones*.

Coal may be defined as an accumulation of mineralized vegetable matter, which has lost much of its oxygen, and has been compressed into a rocky substance. In chemical composition it differs from wood chiefly in having a less proportion of oxygen and a greater proportion of carbon.

Lignite is intermediate in its character between *Peat* and *Coal*, being quite soft when freshly quarried. *Brown coal* with a dull earthy fracture, and *Cannel coal* with a clean conchoidal fracture, are denser and harder varieties. Ordinary house coal is still harder, and generally breaks into cuboidal lumps, with more or less shiny faces. *Anthracite*, or stone coal, is very hard and heavy, with a glossy lustre, and a more completely mineralized appearance. Jet is a variety of Cannel coal which is capable of taking a high polish. The transition from Lignite to Anthracite by the gradual removal of the oxygen is shown in the following table:—

	Lignite.	Cannel Coal.	Splint Coal.	House Coal.	Anthracite.
Carbon . . .	69·3	66·4	75·58	84·28	91·44
Hydrogen . .	6·6	7·54	5·50	5·52	3·46
Oxygen . . .	22·3	10·84	8·33	6·22	2·58
Nitrogen. . .		1·36	1·13	2·07	0·21
Ash	2·1	13·82	5·46	1·89	2·31

3. *Chemically-formed Rocks.*

By chemically-formed rocks, we mean such as have been deposited or precipitated from chemical solution in water, without the intervention of organic agencies. The three most important are *Rock-salt*, *Gypsum*, and *Dolomite*, and the mode in which these rocks are formed has been described on pp. 176, 209. It was also stated that some *Limestones* have probably been formed in a similar way under certain circumstances, but it is not always possible to distinguish these from such as have been produced by the accumulation of organic remains. That Rock-salt, Gypsum, and Dolomite are all formed by similar processes and under similar natural conditions, is proved by their frequent association with one another.

Rock Salt, or chloride of sodium, is generally found in lenticular bed-like masses of greater or less extent and thickness. In England and Ireland it commonly occurs as

a rudely crystalline mass, which is frequently stained red by the admixture of ferruginous clay; the beds are often from 60 to 80 feet thick, but probably thin out in all directions. In the Carpathian mountains there are a series of salt-beds, which in some places make up a thickness of 1,200 feet, and extend for a distance of 500 miles.

Gypsum, or sulphate of lime, occurs in the same way as rock-salt. The thin beds and veins are generally fibrous, being made up of long acicular crystals, which are disposed at right angles to the bounding surfaces, but in thicker beds the texture is often granular. The gypsum of Montmartre, from which plaster of Paris is derived, is chiefly granular, each bed being composed of many layers of little crystals, slightly differing in colour and texture, giving the mass a laminated appearance. In an instance observed by Mr. Jukes at Montmartre, a bed composed of such crystalline layers was traversed by the cleavage planes of a subsequent and more massive crystallization. The original lamination was not obliterated, though bent and waved, as if slightly disturbed by the formation of the crystalline plates, the angles of these waves having an evident relation to the faces and angles of the superinduced crystalline plates. *Anhydrite*, the non-hydrated form of calcium-sulphate, is sometimes found, but when exposed it absorbs water, and becomes gypsum.

Travertine, or **Tufa**, is carbonate of lime precipitated from chemical solution; it is generally of a yellowish colour, often compact and massive, but sometimes perfectly crystalline. *Stalagmite* is of similar origin and constitution (see p. 148). Many limestones are compacted by a cement of crystalline calcite, infiltrated by the action of percolating waters.

Dolomite, or dolomitic limestone, is of variable chemical composition; the ingredients are the carbonates of lime and magnesia, but the proportions of these minerals vary very much. A dolomitic or magnesian limestone generally has a gritty texture, and is often cellular or cavernous; its colour is usually some shade of yellow or brown. When regularly bedded it often makes a good building stone, but it frequently has a tendency to assume nodular and concretionary forms. These sometimes resemble cannon-balls

scattered through the rock, and are sometimes grouped together like bunches of grapes. This nodular structure may be seen in the cliffs of magnesian limestone near Sunderland, whence balls from three to six inches in diameter may be extracted; these are composed of crystals of bitter-spar radiating from the centre, while the horizontal lines of lamination may be traced running across them, showing that the nodules are of subsequent formation.

We have seen (p. 211) that some dolomites may have been formed by direct chemical precipitation, but others have undoubtedly been produced by the subsequent *dolomitization* of ordinary limestone. It is probable that this dolomitization is effected by the percolation of water containing some salt of magnesia in solution. Cases occur where a portion only of a limestone mass has been thus altered, the dolomite occurring as a broad rib bounded by joint planes; in other cases a single bed, or group of beds, has been dolomitized; the mode of alteration being doubtless determined by the comparative facility with which water could percolate either down the joints or along the bedding planes of the rock.[1] Such dolomites may, of course, be considered as Metamorphic Rocks.

Hæmatite and **Magnetite** sometimes form accumulations large enough to be called rock-masses, and occasionally form the substance of whole mountains, such as that called Pilot Knob in the Rocky Mountains, which consists of hæmatite, and the Magnetberg in the Urals, which is composed entirely of magnetite.

Concretions.

It will be convenient in this connection to give some account of the different kinds of nodules which occur so frequently in stratified rocks, and are known by the name of *concretions*. As this term is often used in a loose and ill-defined sense, we shall here restrict it to such lumps or nodules of mineral matter as have a different chemical composition from that of the rock-material which encloses them;

[1] For an excellent account of dolomitization and the theories proposed to account for it, see Professor Green's "Geology for Students," p. 275 *et seq.*

those nodules which are merely spheroidal lumps of the rock-mass, developed during the process of consolidation, are therefore excluded from the present category. These latter we regard as structural developments produced by physical forces, while the former have been produced by the operation of chemical forces. This chemical action may have operated during the deposition of the bed in which the concretions are found, or during its consolidation, and it is a mistake to suppose that they have been entirely formed by a process of segregation after the consolidation of the surrounding material.

In most cases it is evident that the concretions must have been formed while the enclosing deposit was sufficiently fresh and plastic to allow of free molecular movement within its mass; it has also been proved that many such nodules owe their origin to the decomposition of organic matter, and in these cases the concretions must have begun to form while the rock-mass was still permeated with the water in which it was deposited, and before it had been covered up by any very great thickness of subsequently-deposited material. Organic bodies decomposing on the muddy bottom of a lake or sea evolve carbonic acid, ammonia, and other chemical substances, which react on the substances dissolved in the water, and cause the precipitation of various mineral compounds. Other causes may assist in the production of concretionary nodules, and the whole subject requires farther study and investigation. We now proceed to notice the different kinds of concretions which occur among aqueous rocks.

In Sandstones concretionary nodules are invariably either calcareous or ferruginous. In some sandstones large spheroidal masses of calcareous stone occur, which appear to be portions of the sandstone bound together by carbonate of lime; these often abound in fossil remains, while the loose sand outside does not contain any. Other sandstones contain concretions of iron pyrites, varying in size from mere grains up to masses as large as the fist.

In Clays. There are few large deposits of clay which do not contain concretions of some kind.

Septaria are concretions of carbonate of lime, and occur in many clays, forming large nodules which sometimes

attain a diameter of 2 or 3 feet. They are sometimes solid throughout, but more frequently the interior is split up by numerous cracks, which are generally filled with calcite, forming divisions or *septa*.

Clay-ironstone nodules are of similar construction, but consist chiefly of carbonate of iron mixed with more or less clay and carbonate of lime. When broken open the smaller nodules frequently disclose a fossil shell or leaf which has evidently formed the nucleus round which the ferruginous matter has accumulated.

Phosphatic nodules occur in clays and calcareous shales, and are composed of phosphate and carbonate of lime in variable proportion. Those from the Gault and Cambridge greensand contain from 56 to 60 per cent. of the phosphate, with 10 to 12 per cent. of the carbonate, but the Suffolk nodules are less rich in phosphate with more carbonate of lime, and a considerable amount of iron. They are commonly but erroneously called *Coprolites*.

Marcasite nodules, or balls consisting of that variety of iron pyrites called Marcasite, are also abundant in many clays, especially where organic remains are abundant, and frequently enclose some fossil shell or plant.

In Limestones the concretions are either siliceous or ferruginous.

Flint and Chert are well-known substances; the former is translucent, and consists of nearly pure silica; the latter is opaque, and blended with some calcareous matter; both occur as nodules of irregular, and often eccentric form.

The origin of the flints in the chalk, and of the chert nodules in other limestones, was long a matter of doubt, but recent researches have gone far to explain the process. Dr. Bowerbank was the first to suggest that sponges had been much concerned in the formation of flints; and recently Professor W. J. Sollas has made this more certain, and has given the following explanation of their origin. He thinks that the siliceous spicules of numerous sponges gradually accumulating in the chalk ooze, and in presence of sea-water under great pressure, would enter into solution as organic silica; that where the sponge growth was very thick, it contributed so much silica to this solution as to render it concentrated enough for the deposition of

mineral silica, which replaced a certain amount of the calcareous ooze. The calcareous material thus became siliceous chalk, and ultimately a further deposition of silica replacing the remainder of the calcic carbonate converted the siliceous chalk into the dark flint as we now find it.

Marcasite nodules also occur in some limestones, generally in the form of rounded lumps or balls, which have a radiated crystalline structure internally. Many of those in the Lower Chalk of Folkestone are irregular in form, and seem to have been formed by the pyritization of the siliceous sponges known as Ventriculites. The connection of iron-pyrites with decaying organic matter is so persistent that we may safely attribute all such pyritous nodules to the decomposition of organic bodies.

Potato Stones.—These do not occur in limestones, but are *dolomitized* pebbles of limestone. They are hollow inside, and the cavities are lined with crystals of bitter-spar; the existence of the cavity is probably due to the decrease in bulk which accompanies the transformation of Limestone into Dolomite (see Green's "Geology," p. 277).

B. Metamorphic Derivative Rocks.

In this class are properly included all rocks which have been materially altered, either as regards their physical structure or their mineral composition. The simplest case is when the change has been of a physical character, affecting the arrangement of the mineral particles; this is the effect of the enormous pressure resulting from movements in the earth's crust. This pressure has so compressed every component particle in the rock subjected to it, that they are all elongated in one direction, and the rock, consequently, has a tendency to split in that direction. This tendency to split into layers which are not those of original deposition is called *cleavage* or *slaty-cleavage*, and such rocks are said to be *cleaved*.

Of chemical changes the simplest phase is manifested in the decomposition of certain silicates, some of their bases being removed in solution, and others converted into carbonates. A more complicated process is the complete dis-

integration of all the original mineral constituents of a rock, and the reunion of their elements so as to form new combinations. These changes are often accompanied by the addition of new constituents by the agency of percolating waters, and all such metamorphic processes must be carried on under the influence of heat and great pressure.

It must be remembered that clays have been originally derived from the disintegration of mica and felspar, and sandstones, from the destruction of quartzose rocks. Both clays and sandstones usually contain iron and other substances, such as lime and alkalies, which would act as fluxes, and facilitate their conversion back into mica, felspar, and crystalline quartz. When these constituents are re-arranged in separate layers, so that the rock separates into layers of different mineral composition, it is said to be *foliated* (from *folium*, a leaf).

Without attempting, then, to explain all the details of this metamorphic process, nothing appears more probable than that deeply buried sandstones and shales should eventually be reduced into crystalline or semi-crystalline rocks, very similar to the crystalline igneous rocks from which they were originally derived.

Quartzite.—The metamorphism of sandstone produces a compact granular rock, consisting of partially fused and agglutinated grains of quartz. This must not be confused with the *Quartz-rock* of Australia, and other places, which is not a quartzite, but *vein-quartz*, chemically formed in lodes.

Halleflintas are fine quartzose or siliceous rocks not unlike felstones in general aspect; they may have resulted from the metamorphism of fine-grained felspathic sandstones, or trachytic dust.

Porcellanite and **Argillite** are close-grained flinty, or jaspery rocks, produced by the induration or partial fusion of clays, and are generally green or red in colour. *Lydian-stone* is a black, or brownish-black rock of similar texture, produced by the metamorphism of carbonaceous shale; it often contains crystalline grains of quartz, and must then have been originally a sandy shale.

Slate is a less altered rock, any argillaceous rock exhibiting well-marked *cleavage* being termed a slate, its

peculiar fissile structure having been imparted by pressure; ordinary roofing slates, or clay-slates, are cleaved clays or shales, but some are cleaved and rather metamorphosed volcanic tuffs. The best slates are those in which the original grain of the rock was perfectly even throughout, as in a mass of very fine clay. In such a mass the lamination and stratification are often imperceptible, even when unconsolidated, and will, therefore, be still more difficult of detection when the mass has been converted into slate. Other slates, however, show little parallel bands, varying in colour and texture, which are called the *stripe* of the slate, and mark the layers of original deposition or lamination.

Phyllite is a glossy slate, the metamorphism of which has probable been carried a little farther than usual, and has led to the formation of minute flakes of hydrous mica.

Many slates exhibit signs of further chemical metamorphism in the occurrence of sporadic crystals of staurolite, andalusite, chiastolite, and other silicates of alumina. Mr. J. Clifton Ward has described an excellent instance in Cumberland of ordinary slate passing into chiastolite-slate, and thence into a foliated andalusite-schist, and this again into mica-schist.

Schists.—These are all foliated rocks, splitting into thin layers of different mineral matter, and having different names according to the predominance of one or another kind of mineral.

Mica-schist is the most important and frequently occurring of these rocks. It consists of alternate irregular layers of mica and quartz, the mica generally forming a number of small flakes firmly compacted together, and the quartz being generally in less quantity. The rock often has a minutely corrugated or crumpled structure.

Quartz-schist consists chiefly of quartz with small quantities of mica, &c., and may be regarded as linking the mica-schists with the quartzites. *Andalusite-schists*, *Staurolite-schists*, and the *Spotted-schist* (*Fruchtschiefer* of the Germans) are micaceous schists containing aluminous silicates with flakes of graphite and iron-oxides. Mica-schists developing imperfect crystals of staurolite, and passing into

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staurolite-schists, are found along the borders of the granite mass south of Dublin.

Hornblende-schist contains quartz and hornblende as its essential constituents, the latter commonly occurring in abundance; felspar is not unfrequently present, and sometimes predominates over the quartz. The particles are generally felted together with their longer axes in one direction, so as to give a schistose texture, but some varieties are very massive and hardly give any indication of foliation. *Actinolite-schist* is one of its varieties.

Chlorite-schist, *Talc-schist*, *Epidote-schist*, and *Serpentinous-schist*, are more or less foliated rocks in which these particular minerals predominate, but many so-called chlorite-schists are simply green mica-schists. Garnets and minute crystals of iron or copper pyrites are of frequent occurrence in all schistose rocks.

Porphyroid and *Schalstein* are schistose rocks, the one of an acid, the other of a more basic character, whose origin is rather obscure, but probably in many cases they are volcanic tuffs altered by pressure and some chemical change.

Gneiss.—A foliated rock consisting of quartz, felspar (mostly orthoclase), and mica. Garnet is often present, sometimes abundant, with chlorite, epidote, dichroite, graphite, &c. Sometimes foliation is hardly perceptible, and the rock is then extremely difficult to distinguish from granite. It has, indeed, been asserted that in some localities the one rock passes into the other, such masses being lithologically granite, though petrologically and geographically nothing but gneiss. It is quite possible that at great depths extreme metamorphism may take place, resulting in the partial or complete fusion of certain rocks and the production of such metamorphic or gneissoid granite.

Protogine is one of these massive varieties in which the magnesian mica is considerably altered, and has been mistaken for talc. It is abundant in the Alps. *Granulite* is a fine grained rock consisting chiefly of orthoclase and quartz, rich in garnets, but poor in mica. *Kinzigite* is a variety with black mica, plagioclastic felspar, and numerous garnets. *Eklogite* is a granular aggregate of garnet, smaragdite, and hornblende, forming a beautiful red and green

rock, in which pale blue kyanite and silvery white mica are sometimes additional constituents.

Altered Limestones.—The metamorphism of limestone by heat and pressure converts it into a crystalline rock, consisting of closely-packed crystals of calcite. The well-known *marbles* of Carrara and Paros, used for statuary work, are excellent examples of such crystalline limestones. By heating chalk and limestone under such pressure as should prevent the escape of the carbonic-acid gas, Sir James Hall actually succeeded in converting limestones into hard crystalline marble, and even in reducing them to complete fusion, when they acted powerfully upon other rocks. The chalk of the north of Ireland, where penetrated by dykes of basalt, is altered into a hard grey semi-crystalline limestone in some places, and in others into a coarsely crystalline white marble. In many marbles other minerals, such as mica, graphite, and varieties of augite, occur in the crystallized mass of calcite. *Dolomite* (already described) should perhaps always be regarded as a metamorphic rock, but on this point we cannot as yet speak with confidence. *Ophicalcite* designates a group of rocks, consisting of calcite or dolomite with serpentine or a kindred mineral, which stands in need of investigation. Some are only fragments of true serpentine subsequently recemented by a calcareous infiltration; others, like the so-called Galway serpentine, or Connemara-marble, appear to be of sedimentary origin.

Altered Coal.—Anthracite and beds of graphite result from the metamorphism of coal, but the conditions under which the former has been produced are uncertain; the latter is pure carbon or coal, from which all the oxygen, hydrogen, and nitrogen has been driven off.

Section II. Petrology.

CHAPTER V.

STRATIFICATION.

THE Formation of Strata.—The descriptions given in the first part of this book of the manner in which deposits are formed in the rivers, lakes, and seas of the world are really descriptions of the formation of strata, and we have throughout assumed that the reader has a general comprehension of what is meant by lamination and stratification, so that it is not now necessary to enter into any elaborate definition of these terms.

It is sufficient, therefore, to say (1) that stratification is the arrangement of deposited matter in regular layers or strata; (2) that lamination is a structure possessed by certain strata which separate into still thinner layers or laminæ, each of which is a separately deposited film of sediment.

Laminæ and strata are formed in exactly the same way, by the deposition of successive layers of material, and the difference between them is simply that of the thickness accumulated between the pauses of deposition; these pauses being marked by the planes along which they separate.

All stratified rocks, whether coarse or fine in texture, split into beds or strata, which may be of any thickness from an inch to several feet; but it is only rocks of fine texture which split into laminæ. In some cases fifty or sixty separate laminæ may be counted in the thickness of an inch; in others the laminæ are only discernible as bands of colour, or as forming a kind of grain in the rock, so that it splits most readily in a direction parallel to the planes of bedding.

These general facts of lamination and stratification are represented in fig. 61, where seven different beds succeed

one another in regular order; the dotted beds being meant for sandstones, the lined beds for shales, and the plain beds at the top for limestones.

In the limestones no lamination is visible; in the sandstones it is just visible by the arrangement of the component particles along lines which produce a definite "grain"; lastly, the beds of shale are fissile or divisible into separate laminæ.

Since in one bed or stratum of shale there are a certain number of laminæ, say, for instance, it is composed of fifty such laminæ, and since each of these was separately deposited, it follows that so many separate acts of deposition took place in the making of that single stratum, and that

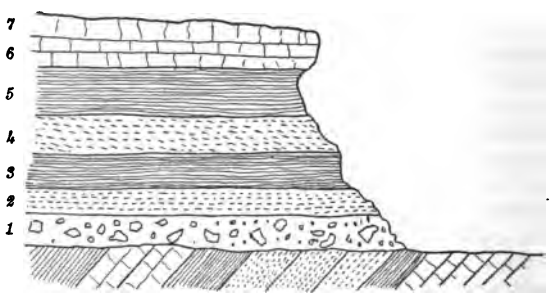

Fig. 61. Lamination and Stratification.

its production was a process involving a considerable amount of time.

Beds which do not exhibit lamination may have been accumulated either more slowly or more rapidly than those which do. The want of lamination may be due to the continual subsidence of fine sediment for a long time without any pause in the deposition, so that the whole forms one inseparable stratum, as, for instance, in the case of the limestone; or it may be due to the rapid accumulation of a large quantity of sediment at once, the result, perhaps, of a single flood, as in the case of some beds of sand or gravel. From the nature of the case, in fact, true lamination is confined to deposits which are accumulated with moderate rapidity, neither very slowly nor very quickly.

Length of the intervals between Beds.—The intervals or periods of non-deposition marked by the planes of separation between beds must vary considerably in length. The interval between the formation of two contiguous beds of similar lithological character is not likely to have been so long as that between beds of different lithological character. In a series of sandstones, for example, the pauses between the deposition of the successive beds may not have been longer than the intervals between successive tides, and it is clear at any rate that the same physical conditions which favoured the deposition of the first bed were continued during the deposition of the succeeding beds.

On the other hand, in such a series of strata as those represented in fig. 61, where each superimposed bed is different to that on which it rests, the intervals between the beds represent pauses during which some change took place in the surrounding physical conditions. Thus, in the case of a shale resting on a sandstone, we must suppose some alteration to have occurred either in the velocity of the currents, or in the geography of the district. The change may have resulted from a diminution in the strength of the current, so that it could only transport mud to the place where it previously brought sand; or from the introduction of a fresh current carrying mud only instead of sand; or, lastly, from the depression of the land whence the supply was obtained, so that the distance from the shore was increased, and only finer sediment could be deposited.

In the case of a sandstone succeeding shale, we should assume the reversal of one of the causes above-mentioned, either an increase in the velocity of the current, or the ingress of a sand-bearing current, or the general elevation of the coast, which would probably change the set of the currents altogether. A limestone resting either on shale or sandstone would lead us to conclude that similar changes were carried on to a still greater extent, till they resulted in the cessation or diversion of all mud-bearing currents, and a long period of rest or slow subsidence ensued, during which the limestone was slowly formed by the accumulation of shells and other calcareous structures secreted by the various animals which lived in the clear waters.

A shale overlying a limestone is, of course, the reverse of the case just mentioned, and the invasion of clear water by a mud-bearing current. Instances sometimes occur where the results of such a change are very apparent. Thus at Bradford, near Bath, the section represented in fig. 62, *a*, may be seen; the lower part being a limestone, on the surface of which there once grew a colony of the peculiar animals called Encrinites, represented in fig. 62, *b*. When alive these animals were fixed to the sea bottom by a solid calcareous base, and on the surface of the limestone these bases are found in great numbers, while scattered in the clay above are remains of the stems and heads of the Encrinites, belonging to individuals of all sizes and ages.

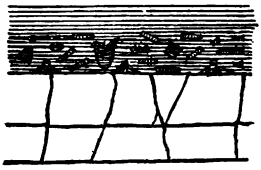

Fig. 62, *a*.

a, Beds of limestone covered by clay, containing Encrinites.

Fig. 62, *b*.

b, Restoration of Encrinites as they lived on the sea bottom.

Now it is plain that in this case, after the limestone was formed, there was an interval during which the sea was quite clear and free from sediment, and therefore well adapted for the growth of these creatures. They settled on the limestone, and flourished there for a sufficient period of time to allow of successive generations arriving at maturity undisturbed, until, finally, the sea bottom was invaded by a current of muddy water, which killed them, and buried their remains in a deposit of mud or clay.

Another example in which the succession of events can be clearly traced is illustrated by fig. 63, which represents part of a quarry in the Isle of Portland.

The lowermost beds in this quarry consist of the Portland Oolite (1, 2), full of marine shells; upon this marine limestone rests a thin seam of black earth (3), full of vegetable remains. Above this are beds of limestone (4), containing fresh-water fossils, and this is succeeded by a thicker seam of vegetable earth (5), full of the roots, trunks, and branches of ancient trees; this is locally known

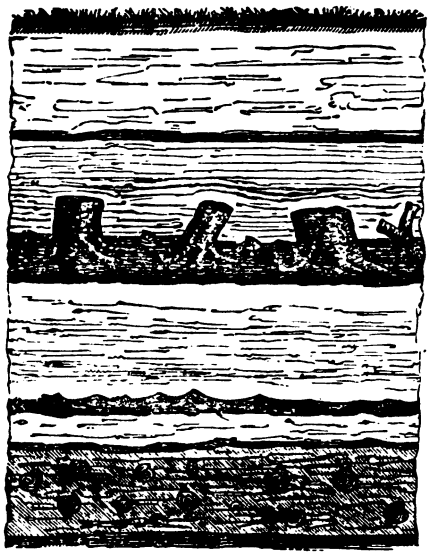

Fig. 63.

as the "dirt-bed." Above come finely laminated limestones (6, 7, 8), of fresh-water origin.

The most remarkable fact here exhibited is the position of the trees in the dirt-bed, for they are still erect in the position of growth, with their roots in the vegetable soil and their trunks extending into the limestone above. The interpretation of these facts is as follows:—

The sea-bottom, represented by beds 1 and 2, was elevated into dry land on which many kinds of plants grew in great luxuriance and contributed their remains to the

formation of the vegetable mould (3). A change then occurred which converted this part of the terrestrial surface into a fresh-water lake, and led to the deposition of the limestone (No. 4). This lake, however, gradually silted up, and part of it passed into the condition of a swamp or fen, which was favourable to the growth of an extensive forest. The lapse of time represented by the accumulation of this little bed of 12 inches in thickness must be very great: time for many generations of trees to grow, flourish, and decay.

Dr. Mantell has thus described the scene presented by the quarry in 1832, when a large surface of the dirt-bed had been cleared for removal.[1] "The floor of the quarry was literally strewn with fossil wood, and before me was a petrified forest, the trees and the plants, like the inhabitants of the city in Arabian story, being converted into stone, yet still remaining in the places which they occupied when alive. . . . . The upright trunks were generally a few feet apart, but 3 or 4 feet high; their summits were broken off and splintered, as if they had been snapped or wrenched off by a hurricane at a short distance from the ground. Some were 2 feet in diameter, and the united fragments of one of the prostrate trunks indicated a total length of from 30 to 40 feet. In many specimens, portions of branches remained attached to the stem. The external surface of all the trees I examined was weather-worn, and resembled that of posts and timbers of groins or piers within reach of the tides, and subjected to the alternate influence of the water and atmosphere; there were but seldom any vestiges of the bark."

It is plain that the forest was destroyed by the depression of the district, and the consequent influx of the lacustrine waters. Layer after layer of calcareous mud was deposited over stems and roots, until the old forest was buried under many feet of limestone. To accomplish this change must have taken many hundreds of years.

The Law of Vertical Succession or Superposition.—The simple facts which have just been described form the basis upon which the whole fabric of historical

[1] "Wonders of Geology," seventh edition, p. 400.

geology is founded. In any succession of beds each one represents the conditions which prevailed over a certain area for a certain length of time; the lowest is the oldest, the uppermost in the newest, and the relative age of the others is indicated by their relative position. In order to mark this fact, geologists are in the habit of numbering such a succession of strata from below upwards, so that if the beds represented in fig. 61 were observed in a cliff they would be described as follows:—

No.	Beds.	Thickness.
7.	Compact limestone . . .	3 feet.
6.	Argillaceous limestone . .	1 „
5.	Laminated shale	4 „
4.	Flaggy sandstone	3 „
3.	Laminated shale	3 „
2.	Fine-grained sandstone . .	2 „
1.	Sandy conglomerate . . .	3 „

Association and Inter-stratification of Beds.—A series of beds which have been uniformly and consecutively deposited generally preserve a certain regular order in their vertical succession. Beds of very fine and very coarse texture are seldom in contact with one another, except where the lower stratum has suffered erosion before the deposition of the upper stratum, which then rests upon a surface of denudation. In a natural and normal series, therefore, deposited during a period of continued depression, conglomerates are covered by sandstones, sandstones are succeeded by shales or clays, and these are followed by marls or limestones, as in fig. 61.

Similarly, if a marine area, on the bottom of which calcareous deposits have been formed, is affected by a movement of elevation, the clear water is first invaded by gentle currents which introduce finely divided mud before it is traversed by those of sufficient strength to carry the coarser material of sand. Pauses in this process, or alternate movements of elevation and subsidence, will, of course occasion corresponding alternations in the succession of deposits.

It is seldom indeed that the change from one kind of deposit to another is sudden and complete; where a sand-

stone passes vertically into a shale, there is usually a space where beds of shale and sandstone alternate with each other; similarly, where a shale is succeeded by a limestone, the lower beds of the latter are usually separated by layers of shale.

Two kinds of rock occurring alternately in this way are said to be interbedded or interstratified with one another, as in the case of the limestones and dirt beds in fig. 63.

In such an alternating series we generally find that there is a certain association between beds of finely divided and slowly accumulated matter, and a similar association of the coarser and more rapidly formed sandstones, pebble beds and conglomerates.

This association of beds is particularly well exemplified in the coal-measures, where a bed of coal almost invariably rests upon a layer of fine clay representing the argillaceous soil upon which the coal-plants grew. This layer is often termed the *underclay* in England, and the *coal-seat* in the south of Ireland. The general order of superposition is, (1) Sandstone; (2) Underclay; (3) Coal; (4) Shale. The roof, or argillaceous bed above the coal, is always more shaly than the underclay, and there is often shale below the latter separating it from the sandstone. This order of succession is illustrated by the following example taken from one of the memoirs of the Geological Survey:[1]—

No.	Beds.	Feet.
15.	Argillaceous shales	64
14.	Coal and shale	4
13.	Coal	1
12.	Underclay	4
11.	Argillaceous shale	4
10.	Sandstone	2
9.	Argillaceous shales	23
8.	Coal	9
7.	Underclay	3½
6.	Coal	0½
5.	Underclay	2
4.	Argillaceous shales	7
3.	Sandstone	1
2.	Argillaceous shale	2
1.	Sandstone	6

[1] "Mem. Geol. Survey," vol. i., p. 210 (Bristol coalfield).

Whether any particular bed is thick or thin depends upon the continuance or interruption of the conditions which led to its formation. For the formation of a great thickness of one kind of rock, it is probably necessary either that the sea in which it is being formed should be very deep, or that the area of deposition should be slowly and continuously subsiding, without causing any material alteration of the currents emanating from the sources of supply.

Thick accumulations of one particular kind of matter are by no means rare. Sandstones often occur in an uninterrupted succession of beds for many hundreds of feet, exhibiting every variety of texture from coarse pebbly beds to layers of the finest possible grain, but without any appreciable admixture of argillaceous matter. Similarly, beds of clay or shale often form a continuous series of great thickness with hardly any intercalations of sandy or calcareous layers. The thickness of certain limestone formations is even greater, amounting, in some cases, to thousands of feet. Thus the chalk of England is in some places more than 1,000 feet thick, and the dolomite of South Tyrol has a thickness of from 3,000 to 5,000 feet.

Horizontal Extent and Thinning out of Beds.—The manner in which mechanical deposits are formed was described in Part I., Chap. XI., and it was especially pointed out that such deposits generally preserved a regular order of succession from the coast outwards, the size of the transported particles decreasing with the distance from land, the finest muds being last deposited, till a limit is reached beyond which no such transported material is found, and its place is taken by sediment of organic origin.

It is clear, therefore, that where such a series of deposits as that represented in fig. 40 has been consolidated and elevated into land, a geologist engaged in tracing the beds across country in one direction, would find them rapidly changing in lithological character; the conglomerates will consist of smaller and smaller pebbles till they pass into coarse sandstones, the sandstones will become gradually of finer texture till, if he can trace them far enough, they will pass into beds of shale or clay. This change some-

times takes place rapidly, and within the compass of a single group of beds; in other cases, beds of sandstone alternate with the conglomerates, and as the latter gradually diminish in thickness, the former thicken and take their place. Similarly beds of shale may alternate and come in between beds of sandstone, and where the shales begin to thin out, beds of limestone may commence and finally take their place.

In one locality, therefore, we may find a series of limestones which may extend over a large area, but when traced in one direction will begin to be separated by little partings of shale. On following the group of limestones and shales still farther we might find that the shales became thicker and the limestones thinner as we proceeded. Finally some of the limestones might thin out and terminate altogether, while beds of sandstone commenced to

Fig. 64.

appear between the shales, until at length the series might consist almost entirely of shales and sandstones with only one or two beds of limestone to represent the purely calcareous group with which we commenced. Under these circumstances we should conclude that we had been approaching an ancient shore-line. Fig. 64 may serve as a representation of the way in which such lateral changes take place, the white bands being meant for limestones, the black for shales, and the dotted bands for sandstones: the figure, however, is a mere diagram, and would have to be drawn out to twenty or thirty times its length before it could be taken as a representation of natural deposits.

Every bed is in fact a great lenticular cake which thins out and terminates somewhere in every direction. As a general rule there is a definite relation between the extent and composition of beds, viz., that the finer the material of which a bed is composed, the wider is its extent and

the more equable its thickness. Individual beds of conglomerate and sandstone are generally thicker than single beds of shale or limestone, but they thin out much more rapidly, while beds of limestone and coal are often persistent over large areas, though they may be only a few feet in thickness.

Mr. Jukes observes that "the extent of single beds is most certainly ascertained in coal mining, in which the horizontal or lateral extension of beds is followed. Particular beds of coal, or of shale, or other rock having recognizable characters, are sometimes known to spread throughout a whole district. For instance, in South Staffordshire, a bed of smooth black shale, a little below the Thick or Ten-yard coal, is known as the 'Table batt.' It has a thickness of from two to four feet, and extends over all the greater portion of the South Staffordshire coal-field —places where it is known being ten or twelve miles apart from each other in different directions. Its original extension was probably much greater, since the beds now disappear in one direction by 'cropping out,' and are buried in others at too great a depth to be followed. Known beds of coal, with a particular designation, such as 'Heathen coal,' extend over still wider areas, and similar facts occur abundantly in most coal-fields. Mr. Hull states that one bed of coal called in part of the Lancashire coal-field the 'Arley Mine,' but known by other names in other parts, spreads over the greater part of the coal-field, which has an area of 192 square miles." [1]

On the other hand, beds of sandstone in the same coal districts frequently thicken or thin out very rapidly. An instance occurs near Wednesbury, in South Staffordshire, where a bed of sandstone known by the name of the "New Mine Rock" thickens out from 9 feet to 78 feet in the course of a few yards horizontal distance. In other parts of the district the sandstone varies from 60 to 15 feet, and in some places is entirely wanting.

A remarkable example of the persistence of the coal-seams for great distances and the impersistence of the mechanical deposits is found in another part of the same

[1] "Manual of Geology," second edition, p. 185.

coal-field. At Essington there is a certain group of "Coal-Measures," consisting of alternations of sandstones, shales, and coals, and attaining a thickness of between 300 and 400 feet. This group, when traced towards the south, thins so rapidly by the gradual dying away of the shales and sandstones, that in the space of five or six miles the different beds of coal come to rest directly one upon the other, and are continued as a compound seam of coal, 30 feet thick, with only a few shaly partings between the beds.[1]

Groups and Episodes.—From the explanations and examples given in the preceding pages it will be evident that when geologists speak of a group of beds, they do not necessarily mean a set of beds of similar lithological composition, but a set of associated beds, connected together both vertically and horizontally, and deposited in contiguous areas during any given period of time. Such a series is found in the Carboniferous or Mountain limestone group. In Derbyshire this consists almost entirely of limestones, which succeed one another in massive beds for a thickness of more than 4,000 feet. When traced northwards, however, into Yorkshire, this great group is gradually replaced by a series of shales, limestones, and sandstones, which form several minor groups or divisions of the series.

Jukes long ago remarked[2] that "it occasionally happens that one large series of beds having a common character includes in some part of it a small, distinct set of beds with a peculiar character of their own," and he observed that some definite term was wanted to designate such an included set of beds. The name he then proposed has, however, been appropriated to express a different idea, and Prof. J. F. Blake has recently introduced the term *episode*,[3] which will probably be adopted as a convenient word for indicating the relation above mentioned.

An episode then may be defined as a small group or set of beds of limited extent possessing special characters which differ from those of the normal series within which

[1] "Mem. Geol. Survey, S. Staffordshire Coalfield," second edition, p. 19.
[2] "Manual of Geology," second edition, 1862, p. 201.
[3] "Brit. Assoc. Rep. (Sheffield)," 1879, p. 33.

it is included. It is, in fact, the lenticular development of a special set of beds formed under exceptional conditions, and therefore differing from those which were formed elsewhere at the same time.

Diagonal or Oblique Stratification.—In fig. 61 the beds are represented as horizontal, each stratum resting evenly on that below; but stratification is not always so regular as this, because the surfaces on which beds are laid down are not always so even and horizontal. For instance, if a current is running over a surface which ends in a slope, the sand, which is being drifted along the bottom, will roll down the slope and remain undisturbed. Layer after layer of sand may thus be deposited in an inclined position according to the slope of the bank. Such a series of inclined strata is often formed where a river enters a lake, as described on p. 172, and is perhaps more frequent in delta deposits than any others, because river currents are, as a rule, more steady and continuous in one direction. An instructive instance has been described by Mr. Jukes in his memoir on the South Staffordshire coal-field. In this case observations in several quarries over an area of at least a quarter of a square mile showed that the beds of sandstone were inclined at an angle of 30°, and it was thought at first that this inclination was due to a subsequent tilting of the strata until another cutting was found, which showed that they rested on a horizontal bed of coal, and that it was merely a case of diagonal stratification. Similarly, near Corsham, in Wiltshire, a group of Oolitic limestones may be seen resting obliquely on other beds of shelly limestone, which are nearly horizontal.

Curvilinear or Irregular Bedding.—This structure is produced under similar circumstances to that just described, but should be distinguished from it inasmuch as it is always a proof of frequent change in the velocity and direction of the currents by whose action the deposits were accumulated. *Diagonal bedding* is produced by the action of a steady current flowing continuously in one direction. *Curvilinear bedding* is caused by the meeting of currents which vary in force and direction from time to time. The term *False-bedding* has been applied to both

structures, but is a misleading term, for both are truly bedded, though the inclination of the beds may be deceptive.

Sir Charles Lyell has described the appearance of a cutting through a sandbank formed near a junction of the rivers Arve and Rhone. where the conflicting currents had produced a series of inclined beds with curvilinear surfaces;[1] above these were more or less horizontal layers, surmounted by irregular alternations of sand and gravel in undulating curvilinear layers. Irregular bedding of this nature is the result of constantly shifting and conflicting currents, and is seldom exhibited by other deposits than those formed in

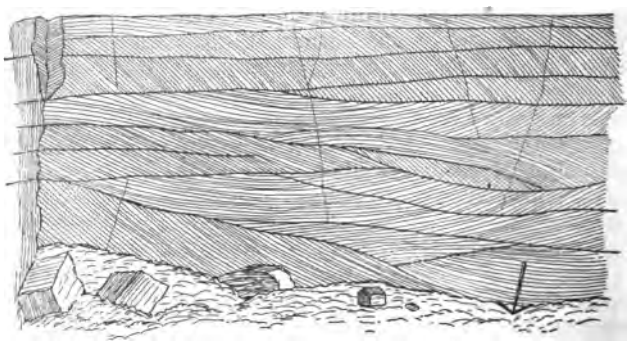

Fig. 65. Curvilinear Bedding in Great Oolite, Minchinhampton.

shallow water, viz., sand and gravel, or sandstone and conglomerate, though it is not unfrequently developed in certain limestones which chiefly consist of the rolled and drifted débris of shells and corals, as, for instance, the great Oolite limestone of Bath and Minchinhampton, and the rock known as the Lincolnshire limestone.

Fig. 65 represents the arrangement of the beds in the face of a quarry at Minchinhampton, as sketched by Mr. Jukes.[2] Part only of the quarry face is shown in fig. 65, the top line being a marked plane of bedding; each bed is

[1] See figure in Lyell's "Principles of Geology," ch. xix., fig. 44.
[2] See "Popular Physical Geology," Jukes, pl. 8.

obliquely laminated, but the surfaces of the beds are all more or less curvilinear; it is evident also that none of these beds are complete, but are portions of so many banks of coral sand formed by the agency of local currents which frequently changed their direction, and constantly removed and re-arranged the materials they acted upon. The contrast and variety is often heightened by differences in the size or colour of the particles composing the different beds.

Current or Ripple Drift.—Another effect of current-action is to be found in ripple-marked surfaces of beds which have been accumulated by the agency of currents in shallow water. The rippled surface is precisely similar to that produced on the sands of a sea-shore by the retiring waters of the tide. Wind moving over the surface of water causes a ripple on that surface. Water moving over the

Fig. 66.

m = ripple marks. b = ripple-drift layers or laminæ.

surface of fine sand causes a similar ripple upon it; not in consequence of the ripple of the wave impressing its form on the sand below, which would be an impossibility, but because the impact of any current on a yielding surface always causes an undulating movement. Where a clear and shallow brook flows over a sandy bottom, the process by which the ripples are formed may easily be watched; the current rolls along the little grains of sand and piles them up into ridges, fresh particles are perpetually moved onwards from behind, are pushed up the slope facing the current, and then rolled down the opposite slope, where they rest so as to form a succession of inclined laminæ or stratulæ. Each ripple is therefore continually advancing on and over the one in front of it (see fig. 66), and thus a series of bands or layers are formed sloping slightly towards the direction from which the material is brought, and consequently in an opposite direction to the inclination of the small stra-

tulæ of which they are composed. Each of these bands ends in a surface ridge or ripple.

Mr. Sorby states that in fine grained sandstones which exhibit ripple-drift, the small stratulæ of sand are often separated by thin layers of argillaceous matter, the different bands being also separated by a similar deposit. He also finds a similar structure in beds of mica-schist where the quartzose folia correspond to the sandy layers and the micaceous to the argillaceous layers, and showing that these schists were originally beds of shaley or flaggy sandstone.

Mr. Jukes observes that in places where the current is troubled, "a modification of these rippled surfaces is sometimes produced, the bed being irregularly mamillated on its surface, which is pretty equally, though irregularly, divided into small hollows and protuberances of a few inches diameter. This surface structure may be seen in process of production now on shores where spaces of sand are enclosed by rocks, so that as the tide falls it is made to run in different directions among the rock channels; but it would probably be caused at any depth at which a current could be similarly troubled and confused. This might be called 'Dimpled current-mark.'"

It must be borne in mind that the rippled surfaces which are formed between tide-marks can seldom be preserved, because the incoming tide always obliterates those previously formed. It is probable, therefore, that the ripple-marks preserved on ancient rock-surfaces have in most cases been formed beneath shallow water at a greater or less distance from low tide level, for a rippled surface may be produced on any bottom over which a current is moving, and such current-marks have in fact been observed beneath water 50 to 60 feet deep. A ripple-mark produced by the tidal current may be covered with the sediment which is deposited during the slack of the tide, and the new surface thus formed may be similarly rippled by the gentle movement of the return current, so that every successive layer or lamina will be ripple-marked. In fine-grained sandstones or sandy shales it is not unusual to find a succession of ripple-marked surfaces, one under the other, at distances of a few inches apart; and the direction of the ripples sometimes varies considerably on the different surfaces.

Mr. Sorby has shown that inferences may be drawn from the examination of these current-marks as to the velocity and direction of the currents which caused them, and that we may thus reason back to some conclusions regarding the physical geography of the district at the time they were formed.

Although, as above stated, ripple-marked beds are not usually such as were formed between tide-levels, yet surfaces are occasionally found which exhibit not only ripple-marks, but also sun-cracks, rain-prints, worm-tracks, and the footmarks of the various creatures which travelled over the moist, exposed surface of the bed. Such surfaces have doubtless been formed on flat shores, where large tracts were exposed between the lines reached by neap and spring tides, so that the surface beyond high-water of neap tides, being exposed to the action of the sun, became cracked and hardened, and the next spring tide only spread over it another layer of sand or mud.

CHAPTER VI.

JOINTS.

IN the last chapter we described some of the structures imparted to stratified rocks at the time of their deposition; but all rocks, whether stratified or unstratified, exhibit other features which have been produced during the process of their consolidation.

There are few exposures of stratified rocks which do not exhibit certain other planes of division besides those of lamination or stratification. These are the *joints*, or long cracks which cut across the bedding planes and separate each bed into blocks of various shapes. It is obvious that in stratified rocks there must be at least two sets of joint planes besides the planes of stratification, in order to cut up the beds into blocks. In igneous or unstratified rocks it is equally obvious that in order to form squarish blocks we must have at least three sets of joints crossing each other, each set more or less nearly at right angles to the other two.

A good-sized clean lump of coal taken from the coal-scuttle forms an excellent model for the exhibition of lamination and joint-planes. If the student will place such a lump on the table before him, he will perceive that the mass is divided by three regular and distinct sets of division planes. "The coal splits most readily along the lines of lamination, and the surfaces thus exposed along the tops and bottoms of the lumps are generally dull and earthy, and readily soil the fingers. At right angles to these surfaces others may be observed, which are generally bright and shining, and if the coal be freshly broken, these surfaces will soil the fingers much less than those on the top or bottom of the lump. He will see that there is one set of smooth, vertical surfaces (or joint planes), along which there occur the cleanest, largest, and most even sides to the block, the vertical surfaces at right angles to that

set being shorter, rougher, and more irregular. The first large, smooth, vertical surfaces are known by the name of *the face, the slyne,* or *the cleat,* of the coal in different districts,—the more interrupted set being spoken of sometimes as the *end* of the coal."[1]

Cause of Joint Structure.—Everyone who has examined the muddy bottom of a dried-up pond or lake is aware that as the water evaporates, and the mud dries, long and deep cracks are formed which traverse the dry mud or clay in various directions, and cut it into polygonal blocks. The width and depth of these cracks seem to depend upon the extent and thickness of the mud.

In the same way molten rock shrinks and cracks in cooling. Attempts have been made to utilize the slags from iron-furnaces by running them into moulds, but the quadrangular blocks so obtained proved to be useless for building purposes because they cracked and crumbled into small cuboidal fragments in consequence of the numerous joints developed during the process of cooling and solidification. Differences in the texture of rocks will naturally cause differences in their manner of cracking, and so different forms of jointing will be produced. The number of joint planes will also partly depend upon the thickness of the bed or mass. Some beds will shrink more than others, and some masses of igneous rock must have cooled more rapidly than others.

Mr. Jukes has remarked that it does not follow that all the joints in any mass of rock should be formed at any one time. "The consolidation of the mass may take place slowly and gradually, and successive sets of joints be produced in it at different times during that process. A rock, moreover, may be, at some subsequent period, placed under circumstances calculated to produce a greater degree of consolidation, and a fresh set of joints may be produced in it from that cause.

"The small or short joints confined to individual beds of stratified rocks may have been those first formed on the original consolidation of the one bed before the next was deposited on it, those joints being then, perhaps, quite im-

[1] Jukes' "Manual of Geology," second edition, p. 212.

perceptible divisional planes with no interspace between the blocks. Whole sets of beds may have subsequently been subject to one, two, or more actions of consolidation, which may have produced larger joints traversing the whole mass. Still more extensive joints may have been formed subsequently by the mechanical agency of the upheaving forces acting on the crust of the globe." [1]

M. Daubrée has lately obtained some curious results by submitting plates of various substances to the effects of torsion, and finding that he could by this means produce sets of cross fractures similar to ordinary joints, he boldly ascribes all joints to the action of force similarly applied.[2] Mr. J. G. Goodchild, however, has recently examined this question,[3] and shows that joints are of various kinds, and are not likely to have all been formed in the same way and by the same force. Some are clearly shrinkage cracks, while the larger "rift-joints" he regards as produced by the unequal pressures and strains exerted upon rock-masses during movements of subsidence and upheaval.[4]

Cuboidal Jointing.—Any mass of stratified rock which is traversed by two sets of joints that are roughly at right angles to one another will fall into *cuboidal* or squarish blocks. This may be seen in almost any stone-quarry, and fig. 67 may be taken to represent a part of such a quarry. The rock-faces, one set of which receive the light, while the other set are in shadow, are the surfaces formed by the two sets of joints cutting the planes of stratification at right angles, and also cutting each other at right angles, and thus making the square corners.

It sometimes happens that small irregular oblique joints more or less obscure the two rectangular sets, and the rock then falls naturally into blocks of various shapes.

In a series of stratified rocks each bed generally has its own system of joints, which are close and regular and do not penetrate the beds above and below. There are always others, however, which are common to several successive

[1] Jukes' "Manual of Geology," second edition, p. 218.
[2] "Geologie Experimental," vol. i., p. 300 *et seq.*
[3] "Geol. Mag.," Dec. 2, vol. x., p. 397.
[4] See also G. K. Gilbert, "Amer. Journ. of Science," ser. 3, vol. xxiv., p. 50.

beds, and seem to have been formed simultaneously, though they often change their direction a little in passing from one bed to another. Lastly, there are some still larger and longer planes of division, which cut through many successive beds, and maintain the same direction both vertically and laterally for very long distances; these are called the *master-joints*. The master-joints sometimes form a more conspicuous feature in the rock than the planes of stratification do, and are occasionally found to cut across whole mountains in regular parallel lines. See the Frontispiece,[1] in which the joints traversing the "Drei Zinnen" in the Dolomite Mountains are well exhibited. These large joints

Fig. 67.

are often open fissures with a space of an inch or more between the walls, and in limestones this space has frequently been widened still more by the action of percolating water (see p. 80 and fig. 17).

Surface Exhibition of Joints.—Although the general characters and vertical course of joints may be readily observed in almost any stone-quarry, there are not such frequent opportunities of studying their horizontal extension or surface exhibition over large areas. Mr. Jukes found that the newly formed beds of stone which occur on

[1] From Prof. Bonney's "Alpine Regions."

some of the coral islands off North-east Australia were already divided by a system of joint-planes. He says:—"I often observed several beds of stone resting on each other, each more than a foot thick, inclined at an angle of 8° or 10°; that is to say, at the same angle as the slope of the beach or bank of sand on which they rested. They had, to all appearance, been consolidated in this position. The joints which traversed them, although often uneven and jagged, ran in straight parallel lines over spaces sometimes of 200 yards, or as far as they could be seen, their planes being generally at right angles to those of the beds, one set of joints running along the greatest linear extension of the mass (*strike-joints*), and the other set directly across the former, and in the same direction as the inclination of the mass (*dip-joints*). The directions of these two sets of joints seemed to depend in these cases on the directions of the principal bounding surfaces or edges of the mass."[1]

The surface exposure of a hard rock like limestone is sometimes so bare of soil as to present an excellent field for observing the horizontal extension of joint-lines, and perhaps no district offers better facilities for such a study than the barony of Burren in county Clare, Ireland. Hills of limestone here rise more than 1,000 feet above the sea, the stratification being almost horizontal, the hill summits and the terraces that sweep round their sides showing broad floors of bare rock over the whole country. The joints, which are very numerous and very regular, have been widened by the rain, so as to form superficial crevices, sometimes several inches in width and several feet in depth. The floors of limestone are cut by them into a number of separate blocks of quadrangular and triangular forms. The late Mr. F. J. Foot, of the Geological Survey, who examined this district, has given a detailed account of these joints in the explanations of the maps 114, 122, and 123, of the Geological Survey of Ireland. He found that there were three distinct sets of joints, besides other small and irregular cracks. Two of these sets of joint-planes were nearly parallel to one another and ran nearly north and south, one a little E. of N., the other a

[1] Jukes' "Manual of Geology," second edition, p. 217.

little W. of N., so as to produce large wedge-shaped blocks, several feet long, ending in angles sometimes as sharp as 5°. These master-joints were crossed by others running nearly east and west, not in straight, but in gently curved serpentine lines. The straight north and south joints sometimes stopped suddenly at one of these cross joints, and it was observable that the neighbourhood of one joint-plane, or the space between two adjoining planes, exhibited a number of closely adjacent parallel joints, not more than an inch or so apart, which split the beds across into vertical slabs.

A similar network of joints is exhibited in many other localities where similar floors of limestone are exposed, the cracks being weathered into deep fissures, while the surfaces and edges of the blocks between them are often curiously rounded and channelled by the rain into an ornamental fret-work, as if the limestone were ice melting in the sun. The interest and singularity of such a scene is heightened by the beauty which is imparted to it by the magnificent ferns and other plants growing in the crevices of the joints, which form natural conservatories to protect the vegetation from rough weather.

The disposition of joints may also be studied on rocky scars, where the surface of one hard bed is sometimes bared for a considerable extent between tide-marks.

Horizontal Jointing.—Besides the vertical joints which are so conspicuous in all stratified rocks, a series of horizontal joints is frequently developed. In many cases it is difficult to distinguish these from the planes of bedding, and probably they are most strongly developed in massive homogeneous rocks which do not exhibit frequent or distinct planes of stratification. They are specially noticeable in the more compact and marly varieties of chalk where the usual planes of bedding are entirely obscured or replaced by a set of irregular and curvilinear joint-planes, which bear some resemblance to those of actual curvilinear bedding produced by current action (see p. 312). Fig. 68 is taken from a sketch in a chalk quarry near Cambridge, where this structure is well exhibited.

A somewhat similar kind of jointing has sometimes been produced in igneous rocks, and has been called "*Cur-*

vitabular structure" by Professor Bonney, who has described an instance in a part of the basalt of the Plateau de la Prudelle, Auvergne. "The mass," he says, "is traversed by a series of more or less horizontal curving joints, with their convexities upward; so that the whole is divided into a series of plano-convex, meniscoid, or concavo-convex blocks, in length perhaps about 2 to 4 feet, and in thickness from 4 to 12 inches. This structure continues with but slight indications of any tendency to vertical master-joints for some 35 feet." [1]

Granite and other igneous rocks often exhibit a much more regular series of horizontal joints, which, together with the vertical joints, split up the mass into a succession of tabular blocks. When these blocks are exposed to atmospheric disintegration, the corners and edges crumble

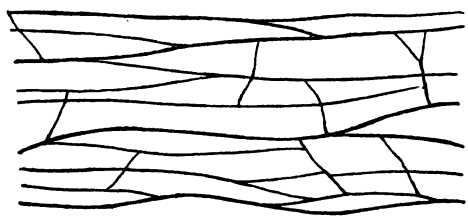

Fig. 68.

away, the joints are widened, and the result is a pile of separate blocks, resting loosely one on the other. In granite districts these piles are called *torrs* or *cheese wrings;* the logging-stones or rocking-stones are also due to the development of a similar structure (see p. 77).

Prismatic Jointing.—Unstratified rocks cannot fall into cubical blocks unless the vertical joints are crossed by another set of horizontal joints. Without these it is clear that the vertical joints will split the mass into long columns or prisms, the shape of which will depend on the number of intersecting joint-planes. This form of jointing has been termed *prismatic,* as tending to the formation of prisms, and it is only from rocks which are thus prismati-

[1] "Quart. Journ. Geol. Soc." vol. xxxii. p. 146.

cally jointed that the great monolithic pillars used for obelisks and other monuments can be obtained.

Granite, syenite, diorite, dolerite and felsite are usually traversed by two sets of joints more or less at right angles to one another, so that the mass is split up into huge tabular blocks or square prisms many yards in length.

Fig. 69 is an instance of such joints in dolerite, sketched by Professor T. G. Bonney, and copied with his permission; some of the great tabular blocks formed by the joints were unbroken from the top to the floor of the quarry, a height of 50 or 60 feet, and stretched still farther down-

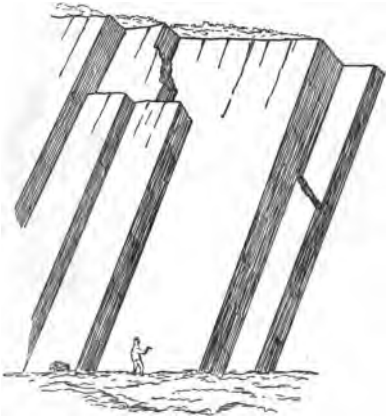

Fig. 69. Joints in Dolerite, N. Queensferry, Fife.

wards, while their faces were as smooth as a plastered wall.[1]

In the granite quarries at Syene (Upper Egypt), whence the ancient Egyptians obtained the material for so many of their monuments, a monolithic block may be seen partially removed from its site, but cracked in the process.

In other cases the continuity of the prisms is broken by the occurrence of a third set of horizontal joints, and the rock separates into rude square-shaped prisms or columns each composed of a number of quadrangular blocks (as

[1] See Prof. Bonney's "Geology," S.P.C.K. series.

mentioned above); this structure is exhibited in some of the granite cliffs between Penzance and the Land's End, and the course of the lines of jointing can be studied in the large quarries at Lamorna.

Another and more regular kind of prismatic jointing is that by which long polygonal columns or many-sided prisms have been produced, such as are shown in figs. 70 and 71; these prisms vary in length from 5 to upwards of 100 feet, and in diameter from 6 inches to several feet.

The Giant's Causeway in county Antrim, and Fingal's Cave in the Island of Staffa are well-known examples of this columnar structure.

The Isle of Staffa is a mass of columnar basalt; it is

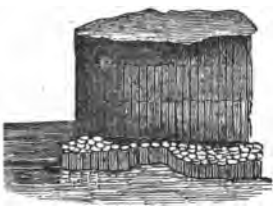

Fig. 70.

Fig. 71.

about two miles in circumference, and forms a table-land of an irregular surface, the greatest elevation of which is about 120 feet. It is bordered on every side by steep cliffs, about 70 feet high, the upper part of which is minutely columnar, while the lower half consists of large polygonal columns. It is intersected by a deep gorge which divides the higher and more celebrated columnar portion from the other division of the island. At the highest tides, the columns which form the south-western cliffs appear to terminate abruptly in the water; but the retiring tide exposes a causeway of broken columns at their base.[1]

It will be observed that in the general view of Staffa, fig. 72, the columns are not everywhere vertical, but in one

[1] See Mantell's "Wonders of Geology," p. 891, from which fig. 72 is borrowed.

part show a tendency to curve away on either side of a medial line. This is frequently the case in other columnar masses, and results from the fact that the joints always strike inwards at right angles from the cooling surface; when,

Fig. 72. View of the Island of Staffa.

therefore, this surface is curved or irregular, the columns are inclined at various angles, according to the directions in which the joint-planes have started from the external surfaces originally bounding the mass of cooling rock.

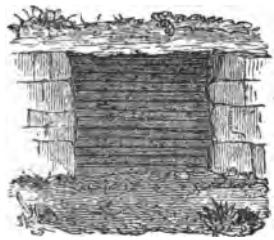

Fig. 73.

Again, in dykes of igneous rock the columns are always at right angles to the bounding walls, and have evidently started from these surfaces where the cooling and consequent consolidation would necessarily commence, as in fig. 73.

Moreover, it often happens that the columns are not continuous across the dyke, but are separated into two sets by a medial plane. In this case it is clear that the columns originating on either side of the dyke struck inwards, and met along the medial line, but a vertical crack or joint-plane having there been produced by the tension of the contracting mass, the two sets of columns could not coalesce into uniform bars.

The columns are generally more or less regularly hexagonal, and Mr. Mallet has shown that on the mathematical principle of least action, a mass of molten rock will naturally tend to break into hexagonal prisms at right angles to the surfaces of cooling. A surface can be divided up completely into the three following equilateral figures, equilateral triangles, squares, and hexagons. Of

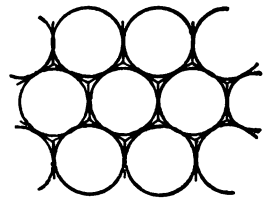

Fig. 74.

these the last, for a given area, has the smallest perimeter; hence, when such a figure is forming by cracking, there will be the least resistance to rupture from the cohesion of the particles of the mass. Again, in the case of the last, it can be shown that, of the contractile force causing the rupture, the component which acts perpendicularly to the sides, and is therefore the efficient part, is the greatest. Hence the amount of work which has to be done in forming a hexagonal column is less than for a square or triangular one.

The contractile force seems to be exerted from a number of nearly equidistant centres, towards which there is a uniform shrinking of the substance, so that every point which is equidistant from three of these centres will be acted upon by three equal forces tending to produce three

cracks of equal length, as indicated in fig. 74. The union of these cracks will form hexagonal figures, and, if the cooling goes on uniformly, the cracks thus commenced will continue to descend into the mass, and will result in the formation of regular hexagonal columns.

The columns are straight and regular in proportion as the cooling proceeded uniformly from a plane surface; but if the cooling surface was convex, the columns must strike inwards towards a centre; while, if it was concave, they would radiate outwards in different directions. Again, the opening of fissures within the mass would provide other cooling surfaces from which independent sets of columns would be started. Thus it frequently happens that in the upper part of extruded bosses or streams of lava, the columns are inclined or curved in various directions, while the lower part of the same mass is regularly divided into straight and vertical pillars; the two portions being separated by a more or less horizontal plane of tension.

Articulated Columns and Spheroidal Structure.—Columnar lavas sometimes exhibit a still more curious and complicated structure, occasioned by transverse articulations or planes of division which traverse the columns at nearly equal distances so as to split them up into a series of separate hexagonal blocks (see fig. 71). The surface of these transverse cracks are sometimes flat, but more often curved, and sometimes they fit into one another with a kind of ball and socket arrangement. Professor Bonney has shown that all these jointed, tabular, and cup-and-ball structures are referable to the same cause, viz., contraction while cooling.

In other cases a spheroidal structure has been developed, the whole mass of rock separating into large balls which exfoliate under the action of the weather into regular concentric layers or coats, like those of a large onion. It was formerly supposed that this spheroidal structure was simply a mode of weathering. It is true that cuboidal blocks of rock, such as those of granite, have a tendency to weather into rough spheroids, and further decomposition might sometimes produce a kind of concentric exfoliation; but this is not sufficient to explain all the instances of spheroidal structure that have been observed.

In the first place, a similar structure is occasionally developed in rocks which are not jointed so as to split into cuboidal blocks; an excellent example of this in bedded shale has been described and figured by Mr. Jukes.[1] Again, spheroids may be found inside a single unjointed prism of columnar rock, instances of which are described by Professor Bonney,[2] and one is reproduced by permission in fig. 75. It was sketched from a mass of columnar basalt near Le Puy in Auvergne, and exhibits several spheroids, one above another, without any dividing cross-joints. "Similar instances of spheroids disconnected from the main joints may be seen in a quarry called Turner's Pit, in the Rowley-Regis basalt (Staffordshire), where, also, in some cases, the nuclei of the spheroids are further subdivided, so that imperfect spheroids are enclosed by a (larger) spheroidal shell like the twin kernels of a nut."

Such instances seem to indicate, as Professor Bonney remarks, that the divisional surfaces of the spheroids and the columns are, to a certain extent, independent of one another, namely, that the cracks opened from without inwards to the less solidified part, and the spheroids, at the same time, formed within this more plastic part of the column, the two surfaces of division running together at last so as to complete the separation.

The precise manner in which these spheroids are developed is not very easy of explanation, but if it be assumed that contraction is taking place uniformly throughout the mass of the cooling material, then spheres may be formed in this mass on the same principle by which hexagons are formed on a plane surface; a sphere being the solid of least superficies for a given volume, and being the figure where the contractile force acts everywhere perpendicularly to the circumference. If the joints simultaneously produced are few and far apart, the spheres will remain spheroidal; but if hexagonal columns are being produced at the same time, the spheroids necessarily come to have a hexagonal circumference, and are regularly superimposed one on another. Whether the top and bottom of each

[1] "Manual of Geology," third edition, p. 311; "School Manual," fourth edition, p. 142.

[2] "Quart. Journ. Geol. Soc." vol. xxxii. p. 151.

block is flat, convex, or concave, depends probably on differences in the strains or tensions within the mass.

Art of Quarrying.—Without natural joints the quarrying of stratified rocks would be very difficult, and that of igneous rocks would be almost impossible, for each block would have to be cut out on every side from the rest of the solid mass. The whole art of quarrying consists in taking advantage of the natural division of the rock by the planes of jointing and bedding, where the latter exist. The shape of the quarry will therefore depend on the direction of the master-joints which traverse the stone. One set of

Fig. 75.

these joints will form what is called the *face* or *back* of the quarry or the boundary wall towards which the men are at any time working; while the other set of joints, at right angles to these, are the planes along which they work; these are called the *ends*, or sometimes the *cutters* of the stone.

In mining operations where adits and galleries are driven into the rock, it is still more necessary to observe the direction of the joint-planes, for by these natural lines of division will the direction of the passages be regulated. This is particularly the case in coal-mining, for, as already stated, beds of coal exhibit not only the ordinary system of distant joint-planes, but also a system of minor joints

which retain their parallelism over very large areas; the main galleries of a coal-mine, therefore, are always driven along the face of the coal, while the cross galleries run along the end of the coal. To attempt to cut galleries across that direction in which the coal will naturally split into blocks would obviously be a much more difficult and expensive task than to take advantage of this structure.

CHAPTER VII.

INCLINATION AND CURVATURE OF BEDS.

WE could not continue our observations upon stratified rocks very long without perceiving that their beds are not always horizontal, but are, on the contrary, generally inclined to the horizon at a greater or less angle.

We have already seen that in certain cases beds of stratified rock may have been originally deposited on a considerable slope. Such beds, however, can only be of very limited extent, and we can hardly imagine a succession of parallel beds to have been deposited with exactly the same slope; neither is it possible for materials finer than coarse sand to rest on a slope having a greater inclination than 35°. Whenever, then, we find a set of inclined beds maintaining an equal thickness and approximate parallelism over a wide extent of ground, we may feel quite sure that when first formed those beds must have been practically horizontal, and that their present inclination is the result of subsequent movement. They must have been tilted, either by being lifted up at one end or depressed at the other, and in many cases the beds have been subjected to such powerful and long-continued movements that they are tilted up at very high angles, and in some cases are set on edge in an absolutely vertical position.

Dip and Strike.—The inclination thus given to beds of rock is called their *dip*; its amount is expressed by the number of degrees contained in the angle between the plane of the beds and the plane of the horizon, and the instrument by which this angle is measured is called a *clinometer*.

Clinometers are made in various ways, but the simplest form is that shown in fig. 76. It consists of a strip of

wood on which is engraved a semicircle graduated into degrees, with a pendulum or plumb-line fixed in the centre of the arc. When held horizontally the plumb-line will be at 0; when inclined to either side it will indicate the angle which its upper edge makes with the plane of the horizon. If, therefore, the clinometer is held so that its upper edge is parallel to the lines of bedding, the amount or angle of dip is easily read off.

The appearance of an inclined bed at the surface is called its *outcrop* or *basset*, and the line along which the upper surface of a bed rises from beneath another is called the *line of outcrop*. The line of its lower surface is sometimes called its *boundary*, but this boundary line must

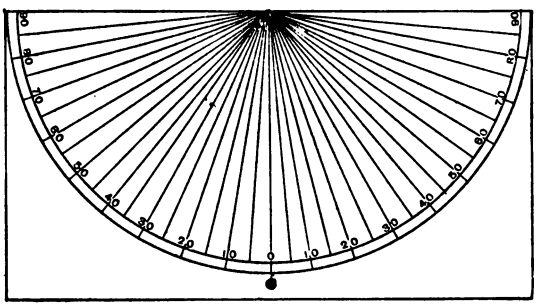

Fig. 76.

necessarily coincide with the line of outcrop of the subjacent bed.

The line at right angles to the plane of the dip is called the *strike* of the bed. The line of strike is in fact the intersection of the plane of the horizon with the plane of the dipping stratum. The strike is always in the plane of the horizon, while the outcrop may be diverted by any irregularities in the surface of the ground; hence the line of strike will only coincide with the line of outcrop when the surface is level and horizontal.

Sir Charles Lyell compares dip and strike to a row of houses running east and west, "the long ridge of the roof representing the strike of the stratum of slates, which dip

on one side to the north, and on the other to the south." The line of strike, however, is not always a straight line, because any change in the direction of the dip will produce a corresponding change in the direction of the strike.

If we know the direction in which a bed dips, we know also the exact bearing of its strike, but if we only ascertain the strike, we cannot also infer the direction of its dip, because it may incline to either side of the line of strike. In geological surveying, therefore, it is most important to observe the dip of all stratified rocks, and to note its direction accurately; it is also important to know its amount, or at any rate to ascertain the average angle at which any group of rocks is inclined.

Geological Map and Section.—Any exposure of rock at the surface, from which the nature and relative position of the beds can be ascertained, is called by geologists a *section*. The exposure may be an artificial opening, such as a quarry, mine, or railway-cutting, or it may be a natural section, such as the bank of a brook or the face of a cliff. These sections are what a geologist first seeks for and studies when he wishes to learn the subterranean structure of a district. By piecing together the information obtained from such isolated exposures he is able to construct a geological map of the district in which he is placed, and also to draw a continuous section through any part of it representing the arrangement of the rock beds as they would appear if some giant hand were to make a vertical cut or trench through the country from the surface to the "sea-level."

Fig. 77 is a diagrammatic view of the Isle of Wight, illustrative of the appearance it would present if all the surface soil was removed, and the landslips of the Undercliff were cleared away, so as to expose the actual outcrops of the different beds over the southern half of the island. Moreover, a huge slice is supposed to have been cut out of the centre, so as to exhibit a vertical section through the island from north to south.

The beds which compose the southern half of the Isle of Wight have been grouped into the following divisions:—

5. Chalk at the top.
4. Sandstone and chert = Upper greensand
3. Blue clay = Gault.
2. Sands and sandstones = Lower greensand.
1. Clays and limestones = Wealden.

It is seen that the beds composing these groups are nearly horizontal in the foreground, but that as they are traced northward toward the centre of the island they begin to dip, the upper surface of each division being brought down to the level of the sea, and the topmost beds of the chalk passing beneath those which form the northern part of the island, and are named Tertiary.

Fig. 77 is the representation of a geological model in relief, but a geological map is only an ordinary map coloured so as to indicate the outcrops of the principal rock-groups. To construct such a map we proceed as follows:—Taking a good map of the district we wish to examine, together with a clinometer and a pocket compass, we search for all the natural and artificial sections. If the district be near the coast, the sea-cliffs will probably afford the best sections, and it will be desirable to ascertain the succession which they exhibit before attempting to map the country inland.

We will suppose that along a certain part of the coast we found a regular succession of beds, steadily dipping one under another in a certain direction: the rocky scar at low tide showing us the exact direction of their strike, the cliff section enabling us to measure the exact angle of their dip. Suppose, too, that the beds fell into five natural groups—1, clays and ironstones; 2, shales; 3, sandstones; 4, shales; 5, limestones; each set of beds having some peculiar characters of its own by which we should readily recognize them again.

When, therefore, we came to trace the beds inland and found a quarry where the sandstones (3) were exposed, we should naturally expect to discover indications of the shales above and below them somewhere on either side of the quarry. If further search in one direction disclosed crags of the limestone (5) on a hill side, and in the opposite direction a brickyard in clays similar to those of group 1,

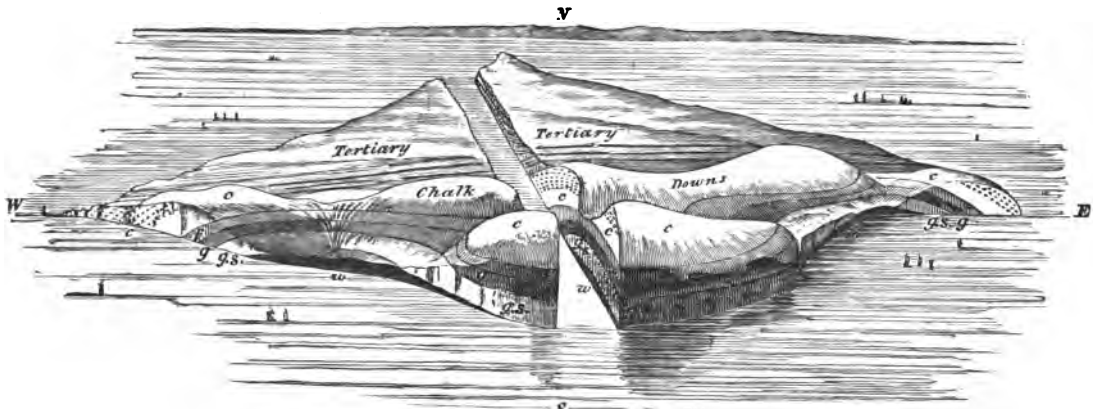

Fig. 77. Diagram of the Geological Structure of the Isle of Wight.

c, Chalk. *f*, Upper greensand. *g*, Gault. *gs*, Lower greensand. *w*, Wealden.

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we should feel sure that the structure of the country inland was the same as that of the shore which we first examined.

It is in this way by gaining a knowledge of the true succession of a series of beds where they are plainly exposed and then following them up across the country, searching for all the small and partial exposures that occur in the banks of brooks, rivers, and valleys, in quarries and excavations of all kinds, and thus carrying on the lines of outcrop from one place to another, that a geological map is constructed. The spaces occupied by the several rock-groups on the map are then coloured so as to be easily distinguished. For further information on the methods of geological surveying we must refer the student

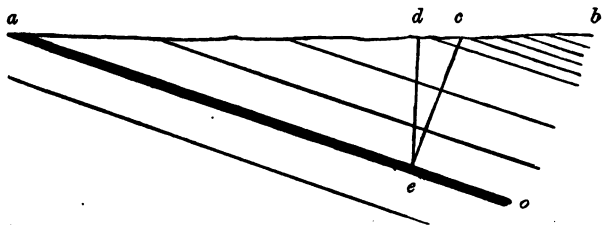

Fig. 78. Measurement of depth and thickness.

to one of the following works—Geikie's "Outlines of Field Geology," or Penning's "Textbook of Field Geology."

As soon as the mapping of any particular district has been completed, a geological section can be drawn across it so as to illustrate its subterranean structure. To do this we must first ascertain the outline of the ground along the line of section; for this purpose the sea-level is taken as a datum or base-line, and some levelling instrument is used by means of which the differences of level can be measured. This process is also explained in the treatises already referred to.

The surface line, *a*, *b*, in fig. 78 may be taken as representing the outline of the ground along the line selected, and knowing from the completed map the exact distance between the points where the upper and lower boundary

lines of each formation cut the line of section, we can draw lines from these points with the observed inclination, in this case at 20° to the E.S.E.

When such a section has been constructed and drawn on a definite scale, the total thickness of the beds exposed at the surface can easily be calculated. Thus supposing the section, fig. 78, to be drawn on the scale of one mile to an inch, the thickness of the beds which come to the surface between the points *a* and *c* is shown by the line *c e* drawn at right angles to their dip; the length of this as measured by a scale is $\frac{3}{4}$ of an inch = 1,320 yards = 3,960 feet, while the breadth of ground occupied by their outcrops measures exactly three times as much.

Moreover, it is evident that we can also ascertain in the same manner the depth of any given bed below any point along this line of section. Suppose, for instance, that *a o* is a bed of ironstone, and that we wished to determine the depth at which it would be found in a perpendicular shaft below the point *d*. By scaling off the length of the vertical line under *d*, this depth is found to be about $\frac{5}{8}$ of an inch, *i.e.* 1,100 yards.

To make such a calculation it is not, of course, necessary to construct a section on a definite scale. It is only necessary to observe the angle of dip and to measure the distance of the given point from the outcrop of the particular stratum, and the desired depth can be ascertained trigonometrically by the solution of a right-angled triangle of those dimensions. To save trouble reference is generally made to a depth and thickness table, which gives the thickness measured at right angles to the dip, and the depth measured at right angles to the horizon, for every angle of inclination that any given bed will attain in a horizontal distance of 1,000 (feet, yards, &c.), measured directly across the strike.

DEPTH AND THICKNESS TABLE.

Horizontal distance = 1000.

Angle of Dip.	Depth.	Thickness.	Angle of Dip.	Depth.	Thickness.
1	17	17	16	287	276
2	35	35	17	307	292
3	53	53	18	318	309
4	70	70	19	345	326
5	88	87	20	366	342
6	106	105	25	469	423
7	123	122	30	580	500
8	141	139	35	705	574
9	160	157	40	842	656
10	177	174	45	1000	707
11	195	191	50	1190	766
12	214	208	55	1430	819
13	232	225	60	1740	866
14	252	242	65	2140	906
15	269	259	70	2750	940

Folds and Flexures.—Although beds sometimes continue to dip at nearly the same angle for several miles, yet it will generally be found that the whole series is bent into a great curve, so that in crossing their lines of outcrop we shall come to a point where the beds dip in an opposite direction. In low countries and broad table-lands these curves are sometimes only gentle *undulations*; elsewhere more decided folds and flexures occur, while in mountain regions the rocks are often bent or crumpled into a series of wonderful convolutions or *contortions*.

When these folds are on a large scale they are spoken of as anticlinals and synclinals; an anticlinal fold being that in which the beds are bent upwards into the shape of an arch or saddle, and a synclinal fold where they are bent downwards as into a trough. Such curves are always supposed to be bent upon an imaginary line which is called the axis of the curve; thus in fig. 80 the axis of a synclinal curve is intersected at the point S, and the axis of an anticlinal curve at the point A.

Fig. 79 is an ideal plan of a district to show the way in

which the outcrops of beds that are bent into anticlinals and synclinals are repeated on either side of the axis; it is part of a geological map in fact, markings or patterns serv-

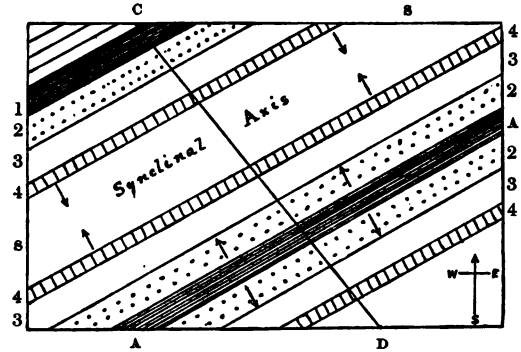

Fig. 79. Plan of Beds bent into an anticlinal and synclinal Curve.

ing the purpose of colours, and fig. 80 is a section across it along the line C D.

The beds are numbered from below upwards, and it is evident from inspection that the beds or groups of beds, 1, 2, 3, are repeated on either side of the synclinal axis, S S,

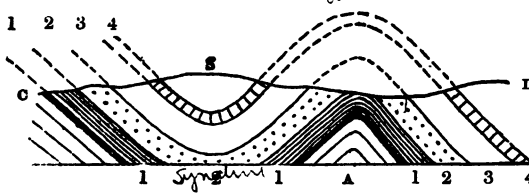

Fig. 80. Section along the line C D in fig. 79.

and that the groups 2, 3, 4, are repeated on either side of the anticlinal axis, A A. The arrows point in the direction of the dip, and the actual dips are seen in the section, fig. 80, where the line C D is the surface of the ground.

In figs. 79 and 80 the axes of the folds are supposed to be parallel to the general strike of the beds, and consequently

the folding only interferes with the uniformity of the dip; but it often happens that beds are folded into curves the axes of which are nearly at right angles to the general line of strike; in such cases the axes are inclined, not horizontal, and the folding interferes with the uniformity both of strike and dip.

Fig. 81 is a plan or map of a series of beds which have the same general strike as those in fig. 79, viz., from W.S.W. to E.N.E., with a normal dip to the E.S.E., as indicated by the arrows. This strike and dip are, however, interrupted by the anticlinal folds at A and B, which cause

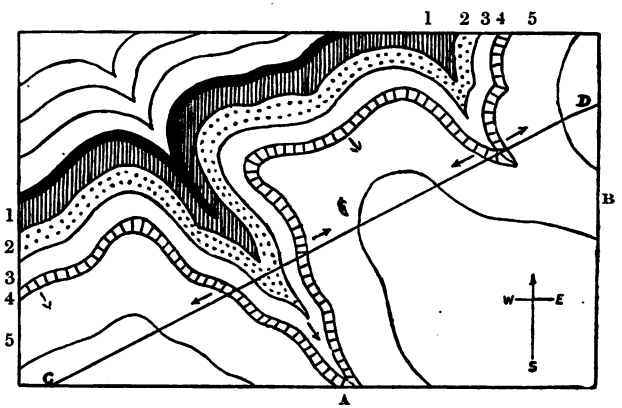

Fig. 81. Plan of inclined Beds folded across the Strike.

the irregularities in the lines of outcrop by bringing up the lower beds, 1, 2, and 3. The axes of these folds are themselves inclined to the E.S.E. with the normal dip, so that where the line of section crosses bed 2 three dips might be observed, one to W.S.W., one to E.N.E., and one to E.S.E.

Fig. 82 is a section parallel to the general strike along the line C D, showing the dips produced by the anticlinal axes. A section anywhere at right angles to this would of course show only the dip produced by the general inclination of the strata to the E.S.E. Such cross rolls or undulations are of frequent occurrence over the ground occupied by the Jurassic and Cretaceous rocks in England.

Periclinal Curves.—When the axis of an anticlinal or synclinal fold is likewise curved, so that the beds are bent up at each end as well as at each side, oval-shaped domes or basin-shaped depressions are produced which

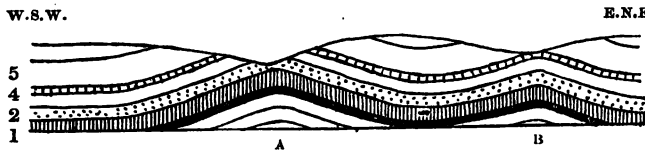

Fig. 82. Section along the line C D in fig. 81.

have a qua-qua-versal dip, and may be called *periclinals*.[1] Fig. 83, is a plan or map of a periclinal basin formed by the outcrop of a series of beds which everywhere dip inwards towards a centre, as shown by the direction of the arrows. These outcrops run in concentric rings or bands

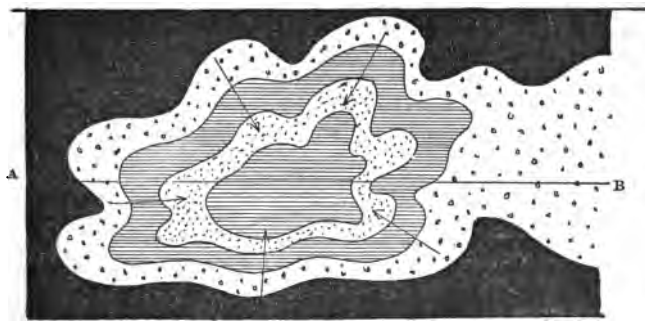

Fig. 83. Plan of a periclinal Basin.

round the central area formed by the highest member of the series. Fig. 84 is a section along the line, A B, and shows the manner in which the strata forming these concentric

[1] This term was proposed by Dr. Page in his "Textbook of Geology," and adopted by W. Topley in his "Geology of the Weald, Geol. Survey Mem." p. 216.

bands crop out to the surface; a section taken along any line across the periclinal would present a similar appearance.

Monoclinal Curves.—When a set of horizontal beds is suddenly bent up or down into a sharp curve, and then continued horizontally at a higher or lower level, the flexure is called a *monoclinal* or *uniclinal* curve, like that at either end of fig. 85. In the Isle of Wight, for instance, the strata which form the hills in the southern part of the island are horizontal, but in the middle of it they suddenly

Fig. 84.

plunge down at a very steep angle to the north, and then pass horizontally below the newer beds which form the low ground in the north of the island (see fig. 77).

Even if the beds are bent back again by a second corresponding flexure, so as to resume their former level, the form produced is not an arch, and though it might be called a flat-topped anticlinal, yet it is better to consider it as a combination of two monoclinals.

The region of the Colorado Plateaux in North America affords many instances of single and double monoclinal

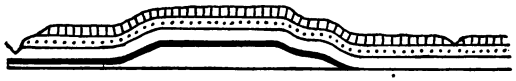

Fig. 85. Diagram of the Structure of the Kaibab Plateau, Colorado.

curves. The great features of the country, in fact, depend upon them, for the strata are horizontal except where they are bent upwards or downwards by such curves (see fig. 85). The country is thus divided into great blocks, several miles in breadth and many miles in length, which have been unequally lifted, so that each differs from its neighbour in relative altitude. These blocks are bounded either by monoclinal curves or by displacements of the strata (=faults). Fig. 85 is a representation of the Kaibab block, copied from a woodcut in Major Powell's Report of his "Explo-

ration of the Colorado." Its upper surface constitutes the Kaibab Plateau, which has a width of about 15 miles, and the strata of which it is formed are flexed down along both margins. The plateaux which compose the Colorado province reach altitudes of 5,000 to 11,000 feet above the sea, so that some of the *blocks* into which they are divided form true mountain ranges, such as the Uintah mountains.

Isoclinal Curves and Inversion of Beds.—These flexures are in some instances carried out so far, both on the small and large scale, that the beds are more or less inverted, and the lower surfaces of beds may be mistaken for their upper surfaces. Thus, in fig. 86, beds of shale and limestone are bent into folds which are tilted over in one direction, so that the same bed is brought to the surface again and again, and an observer who walked over the ground might be deceived into thinking that he was dealing with a great thickness of beds all dipping uniformly in one direction, until he came across some quarry or open section which showed him the true structure of the country. A structure like this, where the folds are all inclined in one direction, has been termed *isoclinal*. At c the folding has been so great as to produce complete inversion. Such inversion may sometimes be actually seen in cliffs, as in North Devon, or in the sides of mountains, as in fig. 87, which is a sketch of the curved strata seen in certain Alpine peaks by Prof. Bonney.[1] In other cases it requires a more widely extended observation in order to show that the apparent order of superposition is the inverse of that which is to be observed in other localities where the beds are less disturbed.

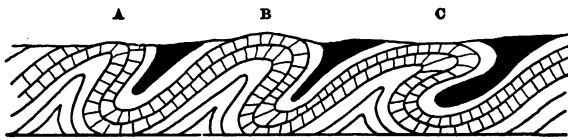

Fig. 86. Isoclinal Curves.

The inversion of beds is occasionally observed in coal-

[1] See his "Alpine Regions," p. 21.

mining, as in Belgium and the south-west of Ireland, where beds of coal are sometimes found with the "coal-seat" or underclay uppermost, and the coal-roof undermost. In such cases, when a vertical shaft is sunk, it frequently happens

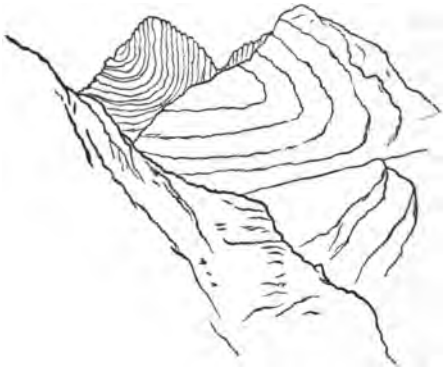

Fig. 87.

that the same bed of coal is passed through a second time at a lower level, the beds below it being a repetition of those that were first found above it. Thus, in a disturbed part of the South Staffordshire coal-field, the same bed of

Fig. 88.

coal was passed through three times in the same vertical shaft, first in its right position, then inverted, and thirdly, right side uppermost: it must, accordingly, have been bent into the shape of the letter S, as in fig. 88.

Fig. 89 is a case observed by the writer in the cliffs between Ilfracombe and Rillage in North Devon. In the face of the cliff fronting the sea there appeared to be three bands of thin-bedded limestone (L) instratified with black shales (B); but the side view, seen in a little cove, showed that there were only two bands of limestone in reality, and that the beds had been rolled together and inverted as represented in fig. 89, *b*.

Contortions.—Large anticlinal and synclinal curves often have minor undulations and flexures on their flanks, and when these are on a small scale, so that several can be seen in a quarry or cliff section, they are termed *contortions*. These contortions are sometimes so close

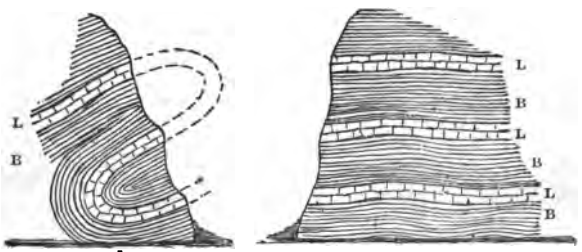

Fig. 89. Inversion near Ilfracombe.
a, Face of cliff. *b*, Side view.

together that the strata look like the crumpled leaves of a book; good examples are figured in Jukes' "School Manual of Geology," 1881, p. 157, and Green's "Geology for Students," 1876, p. 346. Several similar instances are observable in the cliffs near Ilfracombe, and no better coast than that of North Devon could be chosen for studying the effects of flexure, contortion, and inversion. The coasts of Wales, Ireland, and Scotland offer equal facilities for such a study.

Shales which are interstratified with thin beds of limestone or sandstone are sometimes crumpled and folded so sharply as to form a succession of oblique Z's or vandykes; when these are exposed in plan on the sea-shore they look like a series of troughs or boats, each fitting inside the

other like a nest of boxes. In such cases the shales are often squeezed out from between the harder beds so as to form pockets, and Mr. Jukes mentions an instance in the collieries near Kanturk, county Cork, where beds of culm and anthracite, which were originally perhaps 2 or 3 feet thick, expand in some places to a width of 20 or 30 feet, while at others they dwindle down to a single inch.

Fan Structure.—In mountain chains the rocks have sometimes been so folded and compressed that a double series of isoclinal flexures has been developed; the axes of the folds in each series sloping inwards on both sides of a great central anticlinal fold. This arrangement has been termed "fan structure," and is well exemplified in the

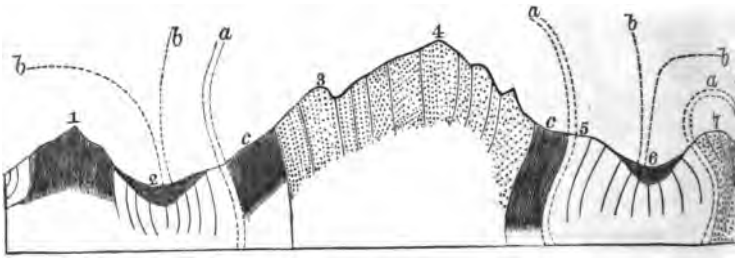

Fig. 90. Fan Structure.

1. Brévent.
2. Val de l'Arve.
4. Mont Blanc.
6. Val de Veni.

Mont Blanc range, through which fig. 90 is a diagrammatic section.

It will be seen that the newer beds (*a a*) actually dip beneath the older rocks forming the central mass, and therefore the relative age of the groups might in such cases be entirely misunderstood by anyone unaccustomed to interpret the structure of mountain ranges.[1] In such compressed and convoluted districts the folds are often puckered by minor contortions and dislocations which add to the complexity of the structure and greatly increase the difficulty of discovering the correct succession of strata.

[1] See "The Secret of the Highlands," by Professor C. Lapworth, in "Geological Magazine," Dec. 2, vol. x. pp. 199, 337.

Cause of Flexures and Contortions.—During the movements of upheaval and subsidence which are constantly taking place in the earth's crust, as described in Part I., Chapter IV., the rocks must necessarily be subjected to great strains and pressures. The probable causes of these movements will be discussed hereafter, the fact of their causing lateral pressures is all that need now be taken for granted.

Though the earth as a whole seems to be extremely rigid, yet the rocks of which the crust is composed are by no means rigid; all clays and shales are more or less plastic, and many sandstones can be bent to a certain degree without fracture. Further, it can be proved that the rigidity of the harder rocks has been caused by the compression of their mass. Hence we may conclude that the earth's crust is plastic within certain limits, and that folding and crumpling of its materials is possible under certain conditions.

It must be remembered that the rocks which now appear so intensely crumpled and contorted have been buried under vast thicknesses of other rocks, and consist of various beds of unequal hardness, which would offer unequal resistance to the force of lateral pressure. Moreover, the disturbances which caused the pressure have been repeated at many periods of geological history, so that the older rocks of a region that has been subjected to many such disturbances are naturally more bent and twisted than the newer beds.

Thus in the south and east of Ireland there are three great rock-groups known respectively as the Cambrian, Silurian, and Carboniferous; it can be shown that the rocks of the first were greatly disturbed and contorted before the deposition of the Silurian, that the latter were similarly contorted before the deposition of the Carboniferous, and that the Carboniferous have also themselves been bent and folded into numerous curves. It is not, therefore, surprising that the Cambrian beds should in many places have been twisted into a confusion of knots and contortions, the unravelling of which would be a perfectly hopeless task.

That contortion is the direct result of lateral pressure

applied under the condition of great vertical weight was proved long ago by the experiment of Sir James Hall. He took pieces of differently coloured cloths, placed them horizontally on a table and covered them by a weight (see fig. 91). He then applied pressure at the sides (*b b*, fig. 92), and found that while the weight was slightly raised the cloths were folded and contorted in a manner exactly analogous to the foldings and contortions observed in nature and illustrated by the preceding figures.

Mr. J. M. Wilson has considered the results of subsidence taking place over a large area;[1] he argues that the borders of that area must be subjected to lateral pressure and that the rocks of those regions must be more or less folded

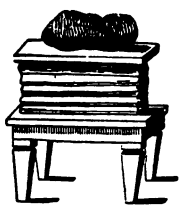

Fig. 91.

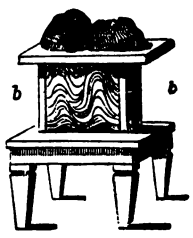

Fig. 92.

Sir James Hall's experiment.

and contorted. He therefore concludes that "*contortions* are the inevitable result of the subsidence of a *curved* surface." Examining this problem mathematically he has constructed a table to show the amount of compression, and consequent contortion, which would result from a given amount of subsidence. He says: "The following are the results I have obtained, on the supposition that a circular area of the earth's surface, whose diameter subtends an angle of 2θ at the centre of the earth, is depressed so as to maintain a spherical form (of course a portion of a larger sphere) to a depth of a miles in the centre of the depressed region. The calculation may be relied on as true within a few yards.

[1] "Geol. Mag." vol. v. p. 206.

TABLE OF COMPRESSION IN YARDS.

For an arc of 2 θ, depressed to a depth of a; radius = 4000 miles.

	$\theta = 5°$.	$\theta = 10°$.	$\theta = 20°$.	$\theta = 40°$.
a = 1 mile	121	211	354	800
a = 2 miles	189	408	745	1625
a = 4 miles	355	788	1584	3214
a = 8 miles	598	1527	3213	8529
Linear distance across depressed area	345 miles	690 miles	1380 miles	2760 miles

"The inspection of this table will show that the known rising and sinking of large areas of the earth's surface is adequate to produce much compression, but it can be made to yield some other important results. When the geological structure of a country is pretty well known, the *amount* of contortion—*i.e.*, the difference between the direct distances of two distant points, (1) measured along a circular arc, (2) measured along strata—may be approximately known. And if this contortion appears not to be due to the intrusion of local igneous rocks, but does appear to be due to depression, we get a means of calculating to what depth the strata sank when these contortions were being produced."

CHAPTER VIII.

FAULTS OR DISLOCATIONS.

IF great thickness of hard and solid rocks can be bent into the curves and contortions described in the last chapter, it may easily be conceived that a different application of the same force would be capable of cracking and breaking through them. We find accordingly that rocks are often traversed by great cracks or fissures, which produce not only a severance, but a displacement of the beds on either side, so that the separated portions are raised or depressed far above or below those with which they were originally connected. These fractures and displacements of large masses of rock are called *dislocations* or *faults*.

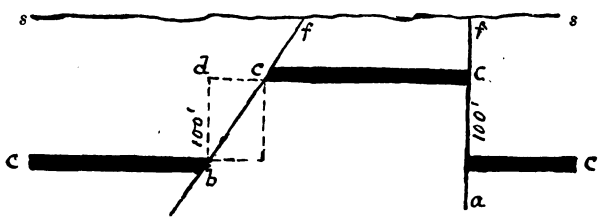

Fig. 93. Faults with the same amount of throw.

Throw and Hade of Faults.—Suppose fig. 93 to be a vertical section through a mass of rock dislocated by two faults, *s s* being the surface of the ground, and *c c* the course of a single bed which was once continuous, but has been broken in two places by the two faults *f a* and *f b*. The two sides of any fault are spoken of as the *up-cast* and *down-cast* sides, though it is generally impossible to say whether the dislocation has resulted from the depression of one side or the upheaval of the other. In fig. 93, the

mass resting upon the base, *b a*, may be supposed to have been bodily upraised.

The amount of displacement produced by a fault is called its *throw*, and is always measured by the vertical distance between the broken ends of any given bed. Where the plane of the fault is vertical, as *f a*, in fig. 93, the amount of throw is easily measured along it; but when the plane of the fault is inclined to the horizon, as at *f b*, the throw is measured by prolonging the level of the given bed till a vertical line will reach its continuation either above or below it. In the case figured the throw of each fault is supposed to be the same, viz., 100 feet. The beds are also drawn horizontal, and when this is the case the amount of throw is also measured by the thickness of the beds displaced by the fault, *i.e.*, the thickness between *b* and *d*.

The student must observe, however, that the thickness

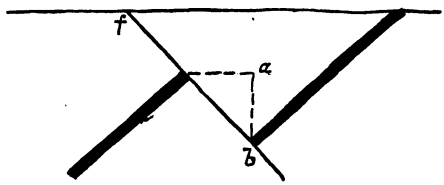

Fig. 94.

of the beds displaced is not always a measure of the throw of a fault; when the beds are inclined, as in fig. 94, the throw of the fault, measured from the level of one end of the broken bed to the level of its continuation, *i.e.*, from *a* to *b*, is evidently less than the thickness of the beds displaced. Whether it is more or less than this thickness will depend on the angle which the plane of the fault makes with the plane of the dipping stratum.

The amount of displacement or "throw" varies from a few feet to many hundred feet; faults involving a displacement of even several thousand feet, having been found in some places, so that rocks of widely different kinds and ages are brought into apposition with one another. Thus, there is every gradation between cracks and fissures, which are merely enlarged joints with hardly

any vertical displacement, and dislocations on the great scale above mentioned.

The inclination of the plane of the fault to the horizon, *i.e.*, from *f* to *b*, in figs. 93 and 94, is called its *hade* or *underlie*. Thus we speak of the *dip* of a bed and the *hade* of a fault. Faults usually hade at a high angle, from 45° to 60° being common inclinations; they are sometimes vertical, as at *f a* in fig. 93, and occasionally the angle of hade is so low as 20°.

There is also a relation between the hade of a fault and the direction of its throw; as a general rule a fault hades under the downthrow side, so that the ends of the severed beds are separated by a greater or less horizontal distance. It also follows under this rule that no part of a severed bed is brought vertically underneath another part of it.

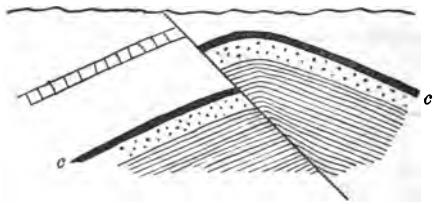

Fig. 95. A reversed Fault.

There are, however, exceptions to this rule, and when a fault hades under the upthrow, as in fig. 95, bringing one portion of the bed, *c*, below the other portion, it is called a *reversed fault*. Faults of this kind are not uncommon where anticlinal folds have been broken and dislocated, and in such cases it would appear that the whole mass of beds on the upthrow side has been pushed up the inclined plane of the fault.

Effects of Faults on the Rocks which they traverse.—Small faults may sometimes be observed where the beds have been broken through so cleanly and evenly that they look as if they had been cut with a knife, the opposing walls of the fissure fitting closely and regularly to one another. More generally, however, the contiguous strata have been bent, crumpled, and pulled down along the plane of the fault to a certain extent, as in fig. 96. The

beds are here represented as bent upon the downthrow side, or in mining language as "rising towards the upthrow," and "dipping towards the downthrow," and this is naturally the most usual effect of a forcible dislocation, accompanied or followed by lateral pressure; but it is not invariably the case, instances occurring where the beds have

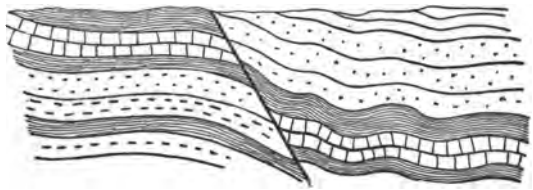

Fig. 96. Flexure of Beds near a Fault.

been bent in an opposite direction, so as to curve upwards on the upthrow side.

Mr. Jukes has described a case of the latter kind as seen in the gate-road of a colliery at Himley in South Staffordshire.[1] The beds here brought into contact by this fault were the Coal-measures and certain red rocks (known as Permian). Mr. Jukes says, "Both formations were greatly

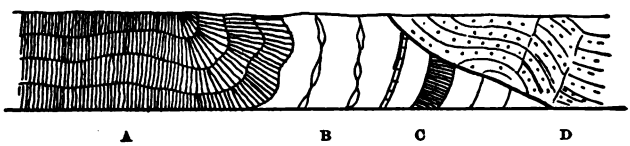

Fig. 97. Section through a Fault at Himley (after Jukes).

A, The Thick coal squeezed and bent upwards; B, Ironstones and shales; C, The Heathen coal; D, Permian beds.

shattered and broken, so much so that no trustworthy determination of the dip of the Permian beds could be made. The coal-measures were not only shattered but squeezed, so that the thick coal lost much of its usual thickness on approaching the fault, and when it came within 10 or

[1] "Manual of Geology," third edition, p. 201.

12 yards of it, it was bent up perpendicularly, and the beds below it rose into the walls of the gate-road, and were cut off above by the red rock lying obliquely across them at an irregular line, the inclination of which to the horizon did not exceed 37°, somewhat as in the preceding figure [fig. 97], which is condensed from a rough sketch and measurement I made on the spot."

Open and Close Faults.—When faults traverse soft and yielding beds of rock, such as shales and thin sandstones or limestones, the fissures themselves are often mere planes of division no thicker than a knife-blade.

When faults traverse very hard and unyielding rocks, such as thick limestones or hard flagstones, and still more if they penetrate hard igneous or metamorphic rocks, the fissures are apt to be much wider and often very irregular. If the original fracture has taken place, not in one plane, but so as to produce two uneven and irregular surfaces, these surfaces, in sliding one over the other, are not likely to fit very closely, but will leave hollows and spaces here and there between the two walls of the fissure.

It is true that the grinding process, as the rock surfaces moved across each other, would often greatly diminish this irregularity, and, in soft rocks, probably obliterate it; but in hard rocks it is usual to find more or less space between the walls of the fault.

In all faults the contiguous surfaces are generally found to be polished and striated by the enormous friction which took place during the movement of one face across the other. These appearances are known by the name of *slickensides*, and it often happens that such slickensides occur on the surfaces of all the joints and cracks for some distance on either side of the fault, and are indicative of the jarring nature of the movement.

It must not be supposed, however, that such fissures are now open and empty. Sometimes they have remained open for a long time, and have been gradually filled up with deposits of crystalline mineral matter, in which case they are converted into lodes or mineral veins; these will be described on a future page. In other cases the spaces between the rock-walls are filled with a confused mass of fragments broken off the contiguous rocks during

the movement of dislocation, mingled with sand and clay, produced by the attrition of these fragments against one another, and the walls of the fault. This mass of fragmentary material is termed *fault-rock*, and is often consolidated into a kind of breccia.

Very large lumps and blocks of the broken beds are sometimes included in this way between the walls of a fault and serve to indicate the existence and direction of

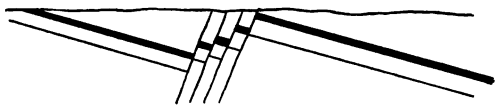

Fig. 98. Compound Fault.

the fracture when it is being traced along the surface of the ground.

Compound Faults.—A long powerful fault is often composed, in the whole or part of its course, of a number of parallel fissures, very close together along a narrow band of country, breaking the rocks into a corresponding number of steps, as in fig. 98, which either *throw* all in the same direction, or else having some steps in an oppo-

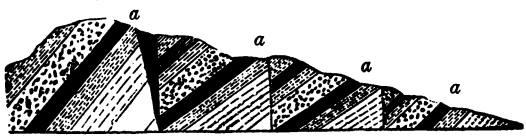

Fig. 99. Step Faults.

site direction, produce a *balance of throw* in one direction, so that it is treated as one wide fault.

Sometimes a set of strata are repeated again and again by a succession of parallel faults much farther apart than those in fig. 98, but hading in the same direction, so as to form a series of broad steps, as in fig. 99. Such step faults might lead an inexperienced observer, who traversed the slope from E. to W., to think that the outcrops of the bed *a* were those of four distinct beds, one passing beneath the other, whereas in reality they are portions of a single bed broken up and carried down to different levels.

If two neighbouring faults *hade* in opposite directions, the two planes must meet along some line below the surface, and will produce what is called a *trough fault*. In such a fault the *trough piece*, as it may be termed, is always let down like a wedge between the outer masses of rock, as in fig. 100.

The opposite faults of a trough may be either unequal in throw, as in the trough A, or equal in amount of throw, as in the trough B. In the former case the displacement along the line, *a*, *c*, affects the whole mass of the surrounding rock, as may be seen by tracing the beds *x* and *z* through the dislocations; in the latter case the displacements counterbalance one another, and affect only the trough-piece B, which is included between the faults.

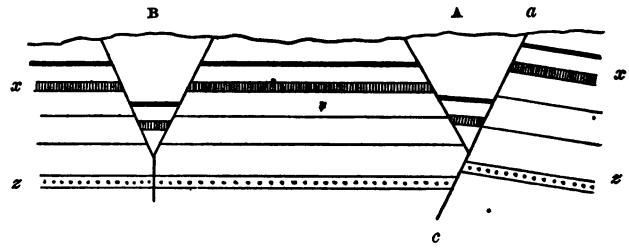

Fig. 100. Trough Faults.

Mr. Topley, however, has pointed out that the appearance of a trough fault may be caused by the displacement of one fault by another.[1] It not unfrequently happens that a district is traversed by two or more sets of faults produced at different times, and if one of the first set be intersected by one of another set, a complicated series of displacements may arise. Thus, in fig. 101, the bed, w, E, was first dislocated by the fault *a*, *b*, *c*, causing a simple downthrow on the W side at *b*. Subsequently a second line of fracture was formed, *d*, *e*, *f*, which hades in the opposite direction, so as to cause a displacement in the plane of the first fault. In the figure this second fault is drawn with a downthrow on the E side, and the result of

[1] "Geology of the Weald." Mem. Geol. Survey, p. 238.

the two fractures is to produce a trough fault, for if the downthrow of the second fault was on the w side, it would be a reverse fault, which is of rarer occurrence.

Effects of Faults on Outcrop.—Since rocks rarely remain horizontal over any considerable area, it is necessary to study the effects produced when a series of inclined or curved beds are traversed by a fault. It is obvious that the displacement must affect their outcrops, but the results produced will vary according to the following circumstances:—1, The direction of the line of fracture; 2, the inclination of the strata; 3, the amount of the vertical dislocation. When the line of fracture cuts more or less directly across the strike of the strata, it may be called a *transverse* or *dip-fault;* and when it is nearly

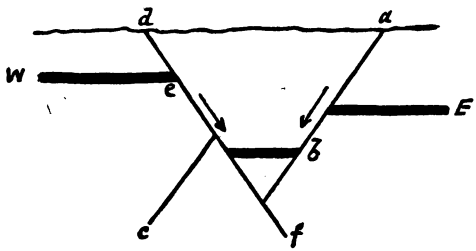

Fig. 101.

parallel to the strike of the beds, it is called a *strike fault.* Those which traverse the strike diagonally may be called *oblique* faults, and will produce a more complicated shift. Most faults, however, may be treated either as transverse or strike faults, and it will be sufficient, therefore, to describe the surface effects produced by these two classes under varying conditions of dip and flexure.

Transverse Faults.—If a set of beds, dipping at a given angle, and striking in a given direction, be traversed by a transverse fault, the effect of the vertical throw is to produce at the surface the appearance of a lateral shift. Let fig. 102 represent the plan of a small tract of country, on which are drawn the outcrops of a certain set of beds, sandstones, shales, and ironstones, having a north and south strike, and an easterly dip as indicated by the arrows.

These beds are broken by two faults, indicated by the lines F, G, the latter of which dies out in the area. The effect of these dislocations is to shift the out-crops to the eastward, but the actual movement was simply a vertical one, both the faults having upthrows to the north, or downthrows to the south, which is the same thing.

It is difficult to make this quite clear to the reader without the assistance of a model, but it would not be difficult for the reader to construct such a model for himself, remembering that after the dislocation is produced, the upheaved piece must be cut through along a plane coinciding with the horizontal surface of the other piece. Suppose such a model to be represented in fig. 103, G H O F

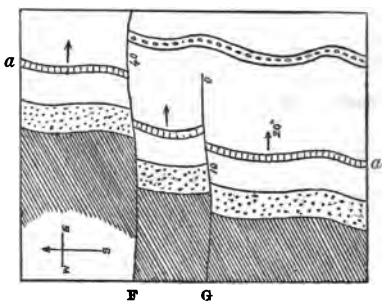

Fig. 102. Plan to show Shifting of Outcrop by Transverse Faults.

being the plane of the fault, the block, A, being on the downthrow side, and the block, B, on the upthrow side of this fault. Let the plane, C D E F, be part of an inclined stratum (say a coal seam) from which the overlying measures have been removed, and the corresponding part of which, on the upthrow side, is the plane, M N O P; the line, M N, having been the continuation of the line of outcrop, C D.

It is clear that if the upper portion of the block, B, is cut off along the plane, G K L, so that the surface of both blocks be again in one plane, then the outcrop of the inclined stratum on the block, B, will coincide with the line, K L, and will be in advance of the outcrop, C D, by the horizontal distance, D K; just as in fig. 102, the outcrop

of the bed, *a a*, is thrown eastward on the upthrow side of each fault.

The effect of the fault may be grasped by the reader if he will hold two flat pieces of wood or cardboard in an inclined position and imagine that they represent the bed of coal indicated by the thick black lines, fig. 103. If he then lift one vertically about an inch above the other, but still keeping them both at the same angle, he will see that if both were intersected by a horizontal plane, the outcrop of one would be in advance of the outcrop of the other.

He will also see that the higher the angle at which the beds dip, the less will be the apparent shift at the surface

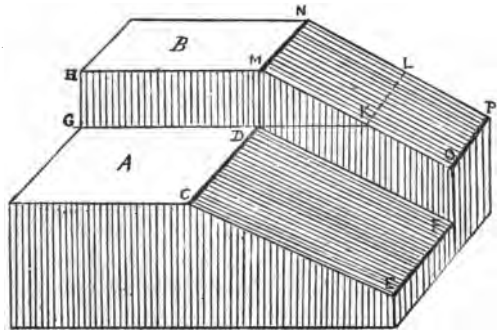

Fig. 103. Diagram to explain Lateral Shift by a Vertical Throw.

produced by the amount of throw. In fact the amount of apparent lateral shift varies directly with the throw of the fault and inversely with the dip of the beds, *i. e.*, the distance between the outcrops *increases* with the increase of the throw, but *decreases* with the increase of the dip.

It is also apparent that if we know the distance between the outcrops of the beds and their angle of inclination, it will be easy to calculate the amount of the vertical throw, and so to discover the depth or distance at which the one part of the bed will be found above or below the corresponding part on the other side of the fault.[1]

[1] It is possible, however, that some dislocations may really be lateral shifts without any vertical displacement. These may be called *heaves*,

That this apparent lateral shift is really due to vertical displacement is more obvious when the fault traverses a district where some of the displaced beds are twice brought to the surface, either by synclinal flexure, or by surface inequalities, as on each side of a hill.

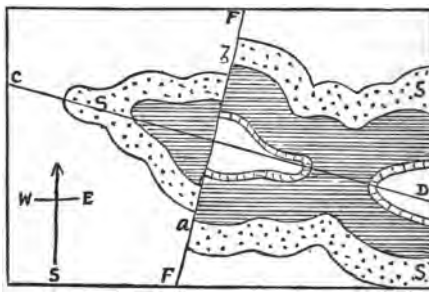

Fig. 104. Effect of a Transverse Fault on Double Outcrops.

Let fig. 104 be a ground plan representing the outcrop of a bed, s s, round part of a long hill or ridge, and traversed by the line of fault, F F. It is evident that if the apparent shift of the bed, s s, on one side of the hill, say at *a*, was due to an actual lateral movement, the outcrop of the bed

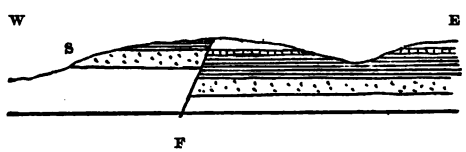

Fig. 105. Section along the line C D.

on the other side (at *b*) would have been shifted in the same direction, *i.e.*, farther north. No kind of lateral movement could possibly bring the two outcrops nearer one another, as is the case on the plan, but the section fig. 105, along the line C D, on the plan, will show that this effect

and they appear to occur in districts which have been much disturbed and fractured; see "Reports of Miners Assoc. of Cornwall and Devon, 1879, Phenomena of Heaves," by A. T. Davies.

is the necessary result of a vertical displacement with an upthrow on the western side. By such a displacement the whole of the block on the west side of the fault is raised so as to bring the bed, s s, nearer the surface of the ground, and, as a consequence, the outcrops of this bed must be brought nearer together. If the fault had been a downthrow on the west the distance between the outcrops on that side would have been increased. In the same way whenever synclinal and anticlinal curves are crossed by transverse faults the distance between the outcrops in the synclinals is lessened and in the anticlinals is increased on the upcast side, while on the downcast side the reverse result is produced. The greater the throw of the fault the greater will be the difference in the distance between the outcrops on either side.

Instances of these effects of tranverse faults will be found by the dozen on the maps of the various coal-fields and other disturbed districts published by the Geological Survey of Great Britain and Ireland.

Strike Faults. — The faults hitherto figured and described are such as cut across the beds so as to interfere with the continuity of their strike; but, as already stated, other lines of fault may run nearly, or quite parallel, to the strike of the beds, so as only to interfere with the continuity of their dip. These are called *strike* faults, and their effect is generally to repeat the outcrops of the beds which are so displaced.

This effect is illustrated by the plan and section, figs. 106, and 107, the plan representing a series of beds striking nearly N.E. and S.W., and dipping to the south-east. These are broken by the line of fault, F F, which is an upthrow to the east, so that where the section is taken along the line C D, all the beds whose outcrop is shown on the western side of the fault are repeated on the eastern side.

Such strike faults are frequently accompanied by a change in the amount of dip, as in the figure, where the dip on the western side is at an angle of 15°, while on the eastern side it is diminished to 10°.

In the above instance the fault is readily detected in consequence of the repetition of the beds caused by the

fact that the fault hades against or under the dip of the strata, and this is most usually the case. There are cases, however, where the fault hades with the dip, *i.e.*, in the same direction, and then, if it also obeys the ordinary rule of hading to the downthrow, an opposite result is produced. Some of the beds are then concealed behind the fault, so as to be prevented from cropping out to the surface at all. Thus in fig. 108 the outcrops of the beds numbered 4 and 5 are wholly concealed from view; and without some natural cross section like that in the figure, such a fault

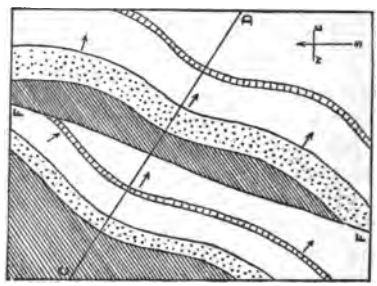

Fig. 106.

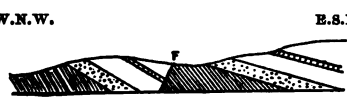

Fig. 107.

Repetition of Beds by a Strike Fault.

would be difficult of detection at the surface, because the surveyor would be apt to think that the beds 1, 2, 3, 6, 7, were in continuous succession, unless he were previously aware of the existence of the beds 4 and 5. The same result would be produced by a reverse fault hading in the opposite direction.

Some strike faults are of very great magnitude, both as regards amount of throw and the horizontal distance over which they extend. As an actual instance of such a fault, we select that known as the Slievenamuck fault in

county Tipperary, which is one of the largest in Ireland. This great fracture extends for a distance of 25 miles, and has a downthrow of nearly 4,000 feet.

Fig. 109 is a section across part of county Tipperary, and represents the dislocation produced by this fault. The rocks displaced by it are (1) certain slates and grits

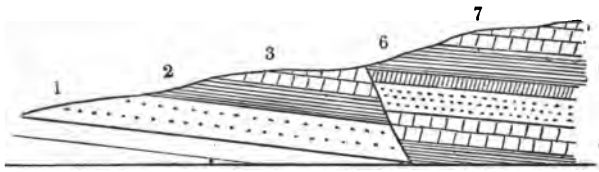

Fig. 108.

known as Silurian rocks, (2) reddish sandstones, called the Old Red Sandstone, (3) grey limestones, called Carboniferous limestone, (4) black shales belonging to the Coal-measures. On the south side of the fault the Old Red Sandstone is found rising steeply from beneath the limestone of the Vale of Aherlow and forming a hill called Slievenamuck, 1,200 feet high. In this hill its beds are

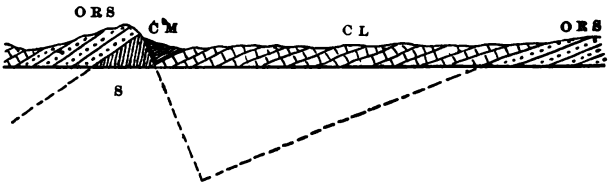

Fig. 109. Section through Tipperary (after Jukes).

C M = Coal Measures. O R S = Old Red Sandstone.
C L = Carboniferous Limestone. S = Silurian.

well seen, nearly from top to bottom, and their total thickness cannot be less than 1,000 feet. On the northern slope of the hill the bottom beds of the Old Red Sandstone are exposed, and may be observed to rest on the uplifted edges of the Silurian slates, which are seen for some depth along the face of the hill. But, on descending the hill a little lower, we come suddenly on to the Coal-measure shales

dipping at a gentle angle to the south, and abutting directly against the Silurian rocks. These shales are about 800 feet in thickness and rest evenly on limestones similar to those in the Vale of Aherlow. Numerous beds of the same Carboniferous limestone crop out to the north, forming the plains of Tipperary, and making up a total thickness of about 3,000 feet. Finally, from underneath these limestones, the upper beds of the Old Red Sandstone again emerge, forming a second, but much lower ridge of hills, which may be called the Emly ridge. The amount of displacement, as measured by the united thickness of the beds which are affected by the fault, is 1,000 + 800 + 3,000 feet = 4,800, and we may, therefore, estimate the vertical throw at about 4,000 feet.

In England the Yale and Bala fault runs from the lowland of Cheshire, through the Hundred of Yale in Denbighshire, through Bala lake and Tal-y-llyn to the sea coast near Towyn in Merioneth, a distance of nearly 66 miles. Its downthrow on the north-west side is estimated to be between 3,000 and 4,000 feet. Another of equal magnitude runs along the western border of the Pennine Hills for 130 miles, and is known as the Pennine fault.

In Scotland a powerful fault crosses the country completely from sea and sea, and separates the ancient crystalline rocks of the Highlands from the newer beds which form the Lowlands. Its length from Loch Lomond to Stonehaven is about 110 miles.

Such faults often form the boundary of one formation or group of beds for a long distance, and are then termed "boundary faults."

Extent and Dying out of Faults.—In cases where the dislocation is affected by a single line of fault, it is clear that the beds must have been bent either upwards or downwards on one side of the fault, or upwards on one side and downwards on the other for a certain distance. Thus in fig. 110 some beds are supposed to have been cracked by the fissure *a b*, and the part *c* to have been bent down, but we might just as easily have supposed the part *d* bent up, or both operations to have taken place simultaneously. Without some such bending no dislocation could have occurred.

The existence of such single-line faults is often proved in coal-mining. Not unfrequently they split towards one or both extremities as in the plan, fig. 111, where the main fault is split into three branches at one end, and two at the other. The figures represent the amount of the down-throw at each point in yards. Such faults generally have one, but sometimes several points of maximum "throw"

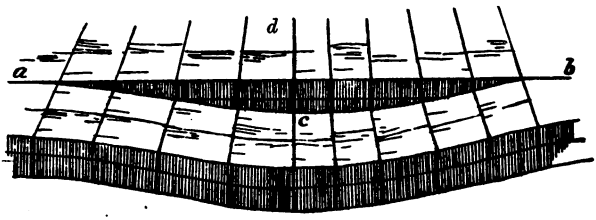

Fig. 110. Diagram of Single Line of Displacement.

near the centre, and gradually diminish each way till they die out. To produce more than one point of maximum throw, we must suppose that there is an undulation of the beds along one or both sides of the fault.

Single lines of fracture are probably much more extensive than the spaces where they are made visible by the dislocation of the beds, since the bending which causes

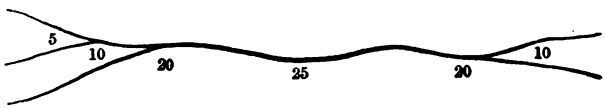

Fig. 111. Plan of Fault splitting at the ends.

dislocation is more likely to occur near the central part of a fracture than near its extremities. Thus in fig. 102 the fracture indicated by the line a is probably continued beyond the point where the line ends, though the actual dislocation ceases there.

When there is more than one line of fracture the fact of dislocation becomes more easy to understand, since there is no difficulty in conceiving that the angle or corner of

ground included between the intersection of two faults, has been dropped down below, or squeezed up above the corresponding beds on the outside of them. In the plan fig. 112, let A B, C D, be two faults meeting in the point D, the included part, E, being depressed below the level of the outside parts. Even in this case, however, the beds inside the two faults must be bent down in the direction of E D, because, as the two faults end or die out at A and C, the whole of the beds must be on the same level there, and gradually change that level in proceeding in the direction E D. The figures as before indicate the amount of throw.

In order to have any mass of beds entirely cut off on all sides from those that surround them, and wholly depressed below or raised above them on every side, it is obviously

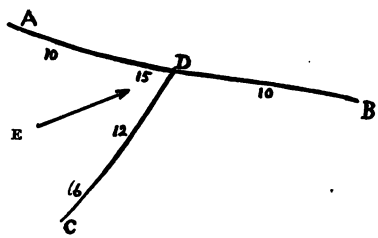

Fig. 112.

necessary that we should have at least three straight faults or two curvilinear faults surrounding the fractured piece of ground. An illustration of an area so faulted is given in Part III., Chapter III.

The Origin of Faults.—The existence of faults has usually been attributed to the contraction of the rock-masses which form the earth's crust. All rocks must contract during the process of solidification,—sedimentary rocks contract in drying, igneous rocks contract in cooling; and thus when rock-masses are raised above the sea-level, and are not subjected to any great pressure, cracks will be found in consequence of this contraction.

Mr. O. Fisher remarks,[1] that "by faulting a portion of the earth's crust is enabled to occupy the same horizontal

[1] "Physics of the Earth's Crust" (Macmillan), p. 208.

area after contracting that it did before, without gaping fissures being formed in it." He points out that if the rock material were perfectly homogeneous, gaping fissures would tend to be formed like those in the mud at the bottom of a dried-up pond, and as these became simultaneously refilled by the settlement squeezing the material into them, it is conceivable that no faulting or displacement need take place. Since, however, the rocks are never homogeneous for any great distance, either horizontally or vertically, it is probable that those on one side of a crack will contract to a greater extent than those on the other side, and the piece or block which contracts most horizontally will also contract most vertically, so that on this theory faults are caused by the depression or subsidence of what is called the *downthrow* side.

Mr. Fisher thinks the fact that faults usually hade to the downthrow may be thus explained. Supposing a gaping fissure to be formed, and the strata on one side (say the east) to settle down more than those on the west, the material on the east side would be pressed out laterally so as to occupy the fissure,—the west side of which, becoming the plane of the fault, would necessarily slope beneath the downthrow piece.

Others[1] have supposed that faults are generally produced during upheaval, and explain the phenomena as follows:—When a portion of the earth's crust is upheaved, the rocks have to occupy more space, and as they are not elastic, they can only yield to the tension by cracking. Once cracked, continued upheaval must cause movement and friction along the plane of the crack, and if this is an inclined plane, the block which has the broader base will be thrust upwards farther than that with the narrower base.

Suppose that in the diagram, fig. 113,[2] we have a section of part of the earth's crust, of which A B, is the surface, and C D, a deep-seated plane, subjected to strains which resolve themselves into an elevatory force, tending to up-

[1] Jukes in "Student's Manual of Geology;" J. M. Wilson in "Geol. Mag." vol. v. p. 206.

[2] This figure is copied from that in Jukes' "Manual of Geology," and the explanation is abridged from that given by the same author.

heave the part A B C D. If, then, a fracture take place along the line E, F, it is obvious that the mass I will present the broader base C, F, for the upheaving force to act upon, and also that this mass grows smaller towards the surface; while the mass K has the smaller base and the wider surface. It is clear, therefore, that it is easier to lift the mass I into the position A C *e f*, than the mass K into the position *g h* B D. The elevation of the mass I would not cause the opening of any gaping fissure, but the elevation of the mass K would produce a great open gap between *e* and *g*, and would leave the projecting piece *g* overhanging without any support. The mass I, therefore, will become the upthrow side of the fault, while the mass K will occupy a lower level, and will form the downthrow

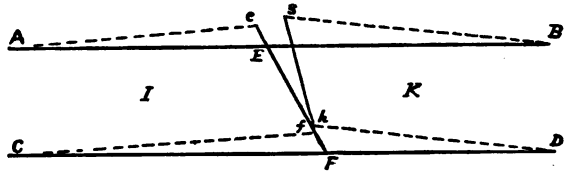

Fig. 113.

side. Hence the rule given on p. 352, that a fault generally hades under the downthrow side.

This is yet more clearly perceptible, if we suppose two such fissures, as in fig. 114, inclining towards each other, since, if we conceive the included piece, C, to be elevated into the position indicated by the dotted lines, it becomes wholly unsupported, unless we suppose huge injections or dykes of igneous rock to issue out along each fault, which would remove the case from the class of fractures we are at present considering. In the case represented by the fig. 114, the masses, A and B, would both be elevated, and the space between them would be widened, so that the mass, C, would be let down along the planes of the two faults, both of which would thus hade to the downthrow.

In this case, also, we have the key to the explanation of certain trough faults; for when the forces of elevation were withdrawn, and the rocks were at liberty to sink down

again, and resume their original positions, the included wedge-shaped mass, w, would no longer fit into the old space, and a process of mutual adjustment would commence, resulting in great compression and great lateral pressure. The reader must recollect that the figs. 113 and 114 are merely diagrams to assist his comprehension, and not actual representations, which would necessarily exhibit a much greater amount of complexity.

It has been said that, in a district which is much broken by faults, the rock-masses between them are not usually much contorted. This may be true to a certain extent, but must not be interpreted to mean that folds and faults are not usually associated. On the contrary, there is a close connection between them; and the two great classes of

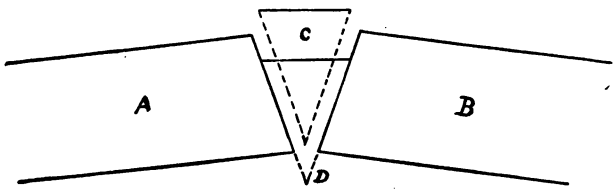

Fig. 114.

faults (*strike* and *transverse*) may be regarded as connected respectively with the two classes of flexures described in the last chapter. In the midland counties of England, where the beds are bent into two sets of undulations, one parallel to, and the other transverse to the general strike, there are also two sets of faults, similarly related to one another. In the Wealden area of Kent and Sussex the majority of the faults have the same strike as the principal folds, viz., from east to west.[1]

It is quite possible, indeed, that many faults are only surface phenomena, and that, if traced downwards into the earth, they would be found to pass into anticlinal or synclinal flexures.

The explanations above given, however, will not apply to all cases; and it is impossible to account for reversed faults, or those which hade to the upthrow by movements

[1] Topley, "Geology of the Weald," Mem. Geol. Survey, p. 237.

of contraction or gradual upheaval. Reverse faults are not unfrequently found in connection with anticlinal curves, as if they had been produced by the same force, namely, lateral compression, and as if the strain of bending had been relieved by fracture.

As far as my experience goes, I think it may also be said that reverse faults are most frequently found in districts which consist of cleaved and contorted rocks, and which have been subjected to great compression. Such faults are, at any rate, not uncommon in the cliffs of North Devon; and I have also seen them among the disturbances produced by the volcanic phenomena of the coast of Fife-shire. Mr. Fisher informs me that he also regards reverse faults as produced by compression.

It appears, therefore, that no one explanation will account for all kinds of faults, and it is probable that different kinds of faults may have been originated by different forces, and that they may be classified as follows:—

1. Ordinary faults, hading to downthrow, are due to contraction of the strata, with or without upheaval.

2. Reverse faults, hading to upthrow, are due to compression.

3. Trough faults, like those in fig. 100, are due to upheaval, followed by partial subsidence.

Mineral Veins.

In studying faults our object has been chiefly to describe their effect in dislocating the beds which they traverse, and only brief mention was made of the minerals which they occasionally contain. It was stated, however, that where faults traversed hard rocks, they are generally more or less open, the walls having been kept apart in some places by their own inequalities. The same is the case with many large cracks and joints in limestone rocks, which have been widened by the action of water.

Now, in many districts, these open fissures have become the repositories of minerals that have been subsequently introduced into them, and they are then termed *lodes* or *mineral veins*.

The minerals they contain are usually in a crystalline

form, and consist of quartz, calcite, barytes, or fluor-spar, together with the ores of one or more metals, such as lead, copper, zinc, antimony, or silver. It is to the metallic minerals that the miner, of course, chiefly looks; and he generally speaks of the earthy minerals as the *gangue* or *vein-stuff*. The mineral contents of a vein are sometimes confusedly dispersed through it, the vein-stuff occupying the chief part of the space, and the ore occurring either as disseminated crystals, or in *nests* or *strings*. Sometimes there appears a regular arrangement of the various substances: the cheeks or walls of the lode being lined with a layer of crystals of one kind of substance, with their points or apices turned inwards, each of these layers being covered by a crystalline layer of another substance, evidently deposited upon the first; and, after two or three such

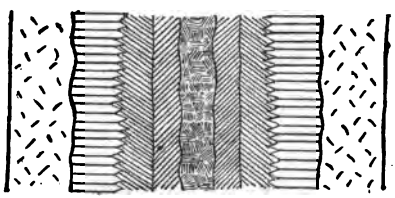

Fig. 115.

alternations, a rib of ore is found in the centre (see fig. 115).

This kind of structure seems to involve the idea of successive depositions of the different coatings or linings of the vein, the central rib of ore being the last or newest. In some cases, it appears that fresh cracks were made by subsequent movements, and that new deposits were found in these openings, slickenside surfaces often occurring on their sides.

The term "lode" is the name applied to such mineral veins in the West of England; but in the northern parts of England they are called *rake veins*, as distinguished from *pipe veins* and *flat veins*, which are only irregular cavernous spaces in the rocks, that have been filled up with mineral substances.

Lodes (or rake veins) vary greatly in width and regularity

—sometimes they continue with an average width of 3 or 4 feet for a great distance, while other veins are subject to *twitches* or closing-in of the walls, which alternate with *bellies* or wide expansions of the vein. When such bellies and twitches alternate very rapidly, they are spoken of as waving veins.

When mineral veins traverse a succession of shales, limestones, sandstones, &c., they are always found to be narrower in the shales and sandstones, and widest in the limestones, being sometimes so squeezed in the shales as to be only 6 inches wide, while in limestone, just above or below, they may be 2 or 3 feet wide. This, as Jukes observes, seems obviously the result of the dissolving power of water acting on calcareous, and not on siliceous rocks, aided, perhaps, by the crushing-in of the softer intervening shales.

It commonly happens that in a district containing mineral veins two sets of fissures can be detected, those of each set being parallel to each other, and crossing one another at a constant angle; the one set are called *right veins*, and the other set *cross veins* or *cross courses*. The two sets of fissures may either be of contemporaneous origin, or one may be subsequently formed.

Where right lodes and cross courses occur together in a district, their contents are often different, one kind of ore being found in the former and another in the latter. Where the date of the cross course is newer than that of the lode, which is often the case, it is easy to understand this difference. When, however, the two veins are contemporaneous, as sometimes happens, it is not so easily understood, but may perhaps be due to differences of temperature in the steam or water by which the minerals were introduced into the fissure.

If a mineral vein be inclined from the perpendicular, and they are seldom quite vertical, it is obvious that any subsequent fracture, producing dislocation, will displace the first-formed lode just as if it were a bed. In the same way its outcrops at the surface will appear to be shifted laterally. Thus in fig. 116, *c c* is a right lode, the course of which is shifted by the fissure or cross vein, *v v*. With regard to such intersections, Mr. Jukes observes that "if

the contents of the right vein are distinctly broken through by the cross course, it is certainly strong evidence that the cross course is newer than the right running vein. If the contents of the cross course be continuous across the interrupted contents of the right running vein, the evidence becomes still stronger;" but it appears that such is not invariably, though very frequently, the case.

It should here be remarked that the hade or inclination of lodes is always calculated from the vertical and not from a horizontal line, as in the case of faults and beds; a slight hade, therefore, answers to a high dip, the one being the complement of the other, a hade of 10° being a dip of 80°.

By what processes the various minerals have been intro-

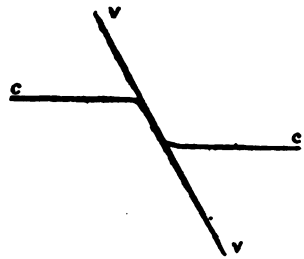

Fig. 116.

duced into veins is a subject on which much has been written, but little is certainly known.

Sir H. de la Beche has pointed out that where warm water is rising from great depths through narrow fissures, it must lose a large amount of heat as it approaches the surface. Consequently those substances which are only soluble at high temperatures, such as silica and many metals, would crystallize out of solution, and would be deposited on the walls of the fissure.

This theory finds support in the fact that mineral veins are being actually formed in certain volcanic districts at the present time. Sulphur Bank, California, is one locality where such vein-formation has been observed.[1] Hot

[1] See paper by Leconte and Rising in "Amer. Journ. of Science," Ser. 3, vol. xxiv. p. 23.

springs, solfataras, and fumaroles are here abundant, and the deposits are clearly due to the uprising alkaline or solfataric waters. At a certain depth below the surface, beyond the influence of atmospheric agencies, the cracks and fissures in the rock are filled with a hydrous silica (opal) in a soft cheesy condition, generally streaked and clouded with cinnabar (sulphide of mercury). In other parts of the mine the silica has consolidated into chalcedony, and the cinnabar is found sometimes in layers alternating with the silica, sometimes lining or filling fissures by itself. Here, therefore, veins with quartz vein-stuff and metallic ore are now actually in process of formation.

It has been found that some relation exists between the mineral contents of a vein and the nature of the rock which it traverses. Some Cornish lodes contain copper ore where the walls consist of slate, and tin ore only where they are of granite.[1] This fact may, however, be explained by supposing that different rocks are capable of determining the deposition of different minerals on their surfaces under the influence of terrestrial electricity.

[1] J. W. Henwood, "Trans. Geol. Soc. Corn." vol. v. p. 190.

CHAPTER IX.

UNCONFORMITY AND OVERLAP.

THAT dry land has always existed somewhere throughout all geological time we know from the very existence of mechanically-formed rocks, which are the memorials of its erosion and destruction. "Lyell long ago showed that the amount of such [detrition and] denudation is to be exactly measured by the quantity of the mechanically-formed aqueous rocks, and as our present lands show us vast sheets of sandstones and clays hundreds and thousands of feet in thickness and hundreds and thousands of square miles in extent, and as every particle of these enormous masses of rock is the result of the erosion of previously existing rocks, it follows that the amount of denudation must have been just as great as that of deposition. Just as when we see a large building we know that a hole or quarry must have been made somewhere in the earth, equal, at least, to the cubical contents of the solid parts of that building; so, where we see a vast mass of mechanically-formed aqueous rocks, we must feel assured that a gap was made somewhere in the surface of the earth equal to the solid contents of those rocks" (Jukes). Conversely, also, when we have ascertained that a large amount of rock material has been removed from any existing, or any ancient land surface, we can be sure that an extensive series of stratified deposits must have been formed somewhere out of the materials thus removed, and that their deposition went on *pari passu* with the detrition of the land surface.

The oscillations of level which have continually taken place have caused frequent changes in the form of the ancient continents, depressing some parts beneath the sea and elevating other parts, so as to raise portions of the adjoining sea bottom into dry land. The tracts that formed dry land were constantly exposed to the detritive action of

those agencies which were described in Part I., Chapters VI. and VII., and the tracts that sank below the sea were subjected to the planing and levelling action of the sea waves (Chapter VIII.).

The result of both processes being to remove a great thickness of rock, and the special result of the latter process being to produce the more or less level surface which is termed a plain of marine denudation, it follows that when such surfaces are depressed far below the sea level, and newer deposits are laid down upon them, there must be a break or discontinuity between the older rocks and the newer deposits. The older series may form a regular and continuous sequence of beds, but the process of deposition having been interrupted by a period of erosion and disturbance, there must naturally be a certain amount of discordance between the older and newer series. Such discordance constitutes unconformity.

The importance of these conclusions cannot be over-estimated, and without a knowledge of the facts and inferences to be described in the present chapter, the student could make but little progress in the study of stratigraphical geology.

Every country has its own geological sequence, comprising a great series of strata, which is divisible into many natural groups or stages, and between any two of these groups there are only two possible relations: they must be either in *conformable* or *unconformable* succession. These terms we proceed to define.

1. **Conformable Succession.**—Two sets of beds are said to be *conformable* when the base of the upper set rests evenly upon the surface of the lower set, that surface being everywhere one of original deposition. The plane of separation between two such groups simply marks an interval of comparatively short duration, during which no deposition took place. Two or more conformable groups of beds will therefore form a regular sequence like that of the groups 1, 2, 3, 4, in figs. 117 and 119.

2. **Unconformable Succession.**—Two sets of beds are said to be unconformable when the base of the upper set rests in different places on different parts of the lower set, the upper surface of the latter being either entirely or

in part a surface of erosion. Such a plane of separation involves the lapse of an interval more or less long, during which parts of the beds previously formed were broken up and carried away, leaving a discontinuous sequence or a discordance in the stratigraphical succession, as in the lower part of fig. 117, where the lower group of beds, *m*, *m*,

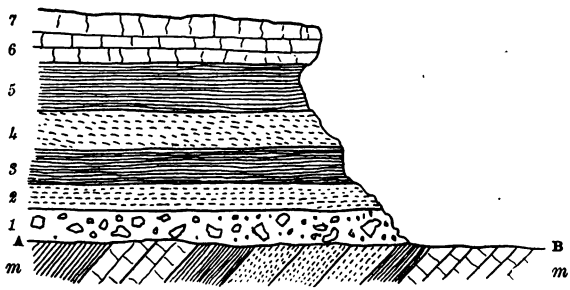

Fig. 117.

have been tilted and planed off till the horizontal surface A, B, was produced, on which the overlying strata 1 to 7 have been deposited.

This definition of unconformable succession is a very general one, and is framed to include cases which are not generally called *unconformities*, though they are *discordances*. There are, therefore, two kinds of discordance, and, as the

Fig. 118.

distinction between them involves important considerations, it is necessary that they should both be clearly defined.

A. *Contemporaneous Erosion.*—This is a partial discordance caused by the erosion of channels and hollows in a lower group of beds before the deposition of the overlying group. Thus in fig. 118, a channel has been eroded out of

the beds, c, c, and the succeeding strata, s, s, have been deposited horizontally upon the uneven surface thus produced. In such cases the erosion has only been local and partial, and no permanent upheaval or denudation took place in the interval. It is obvious, moreover, that if the deposits were subsequently tilted, they would both be inclined at the same angle, and would strike in the same direction.

B. *True Unconformity* involves complete discordance, and may be defined as the superposition of one group of beds upon the upturned and eroded edges of another group (as in fig. 117). In such cases the interval between the

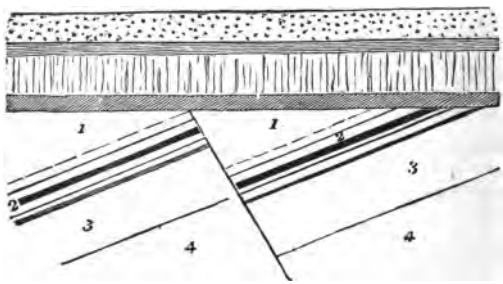

Fig. 119.

two groups must have been long enough for great geographical changes to have taken place; these must have included the elevation of the lower group, the production of a land surface, and the subsequent depression of this surface below the sea. The magnitude or strength of the unconformity depends upon the amount of discordance between the inclination of the two formations, and upon the extent to which the lower rocks were disturbed or altered before the deposition of the upper group. Sometimes the difference of dip is so slight that it only becomes apparent after a large area of ground has been surveyed. In other cases the faulting or flexure of the older beds before the deposition of the newer, as in fig. 119, or their flexure and contortion as in fig. 122, renders the fact of unconformity easy to detect. Finally, if, as in fig. 122, the group, s,

consisted of crumpled and metamorphosed rocks, and the group O R S, of unaltered sandstones including rolled fragments of the metamorphic rocks, the unconformity would be very marked, and we should infer that a long period of time had elapsed between the formation of the two groups.

The occurrence then of a strong unconformity with a marked discordance may in itself be taken as a proof of elevation, denudation, and subsequent depression, and as presumptive evidence that dry land existed there during the interval between the formation of the two series of strata. But a case of contemporaneous erosion only proves that the lower beds have been brought within the action of

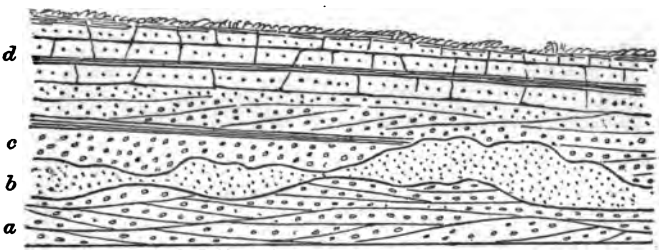

Fig. 120. Contemporaneous Erosion near Nottingham.

currents, without being raised above the surface of the sea in which they were deposited.

Instances of Contemporaneous Erosion.—The subaqueous erosion of a bed can only be effected by currents, and a surface which displays such channels and hollows must therefore have been brought within the influence of currents which only act powerfully in shallow water. Erosion of this kind is consequently an indication of shallow water.

Fig. 120 is an instance observed and described by Mr. J. Shipman, near Nottingham.[1] It will be noticed that the pebble-beds, *a*, have been eroded into hollows and ridges

[1] Quoted by Aveline, "Geology of the Country round Nottingham," p. 28.

before the deposition of the white sands, *b*, which are exceedingly variable in their thickness, because they rest on this uneven surface and have themselves suffered erosion before or during the deposition of the conglomerate which overlies them. This conglomerate passes up into the soft brown sandstones which are locally known as "Waterstones," *d*.

Similar trough-like hollows are met with in coal-mining traversing beds of coal, portions of which are removed and the hollows filled up with clay, shale, or sandstone, the infilling material being usually the same as that which forms the roof of the coal elsewhere. Mr. Buddle has fully described an instance occurring in the Forest of Dean, where the miners gave the name of *the horse* to the mate-

Fig. 121. Rock Fault, or Contemporaneous Erosion of a Coal-seam.
c, Main coal. s, Sandstone.
Length of section about 15 yards.

rial which thus seemed to come down and press out the coal. This trough was found to branch when traced over a considerable area, as in coal-mining it necessarily was, and to assume all the appearance of having been formed by a little stream with small tributaries falling into it; the channels of the stream being afterwards filled up by the subsequently deposited materials which were spread over the whole coal.

In other parts of the country, similar interruptions to the continuity of a coal-seam are called *rock-faults*, though of course they have nothing to do with any kind of fault in the geological sense of the term. Fig. 121 represents an instance which occurred in a coal-seam at Coleorton, Leicestershire. It is part of a channel excavated in the main coal, c, which is here about eight feet thick, and subsequently filled up with the sandstone, s. The component layers of the sandstone are very irregular and obliquely

laminated, another result of current action (see p. 311), which is of course very likely to occur in cases of contemporaneous erosion.

Instances of Unconformity.—1. *South of Ireland.*—We have already had occasion to mention the three great groups of rock which enter into the structure of the south of Ireland (see p. 347), viz., 1, the Silurian; 2, the Old Red Sandstone; 3, the Carboniferous limestone. Between the first and second of these there is a wide unconformity; but the third is always conformable to the second, though it often overlaps it, in consequence of the small area within which the sandstone was deposited, the Carboniferous limestone having a much wider extension.

Fig. 122 is a diagrammatic section across Freagh Hill, a few miles north of Thomastown, in the county of Kil-

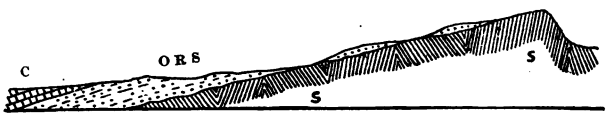

Fig. 122. Section through Freagh Hill (after Jukes).
S = Silurian. O R S = Old Red Sandstone. C = Carboniferous Limestone.

kenny. The Silurian rocks, S S, were disturbed and contorted, upheaved and denuded, and lastly a level surface of planation was formed across their edges during their depression beneath the sea. Upon this surface the Old Red Sandstone was *unconformably* deposited, succeeded *conformably* by the beds of the Carboniferous limestone. Subsequent elevation and denudation has removed all the limestone from the high ground, and also the red sandstone, except one or two patches of it, which now form outliers, and has thus re-exposed the old level floor of Silurian rocks on which the sandstones were deposited.

The boundaries of the Carboniferous limestone and Old Red Sandstone may be followed through the counties of Kilkenny and Carlow, affording the most convincing proof of the great denudation of the Silurian tract, which took place prior to and during the formation of the Old Red Sandstone, even to the extent of laying bare the

granite which lay beneath these older rocks. The continued depression of this old land surface, the subsequent overlap of the Carboniferous limestone, and its deposition on the bare granite, are also demonstrated by the mapping of county Kilkenny.

"Fig. 123 is a diagrammatic section taken a few miles south of Thomastown, where the ancient denudation had

Fig. 123. Section near Thomastown, Kilkenny (after Jukes).
G = Granite. S = Silurian. O R S = Old Red Sandstone.

laid bare a portion of the granite above mentioned.[1] The Silurian rocks are traversed by granite veins in the neighbourhood, and are, near the granite, altered into mica-schist. The Old Red Sandstone, on the other hand, rests upon the granite quite undisturbedly; it is unaltered by that rock, and is obviously made chiefly of granite sand, containing occasionally some granite pebbles, though not so many of those as fragments of the slate rocks, when it rests upon them. The granite is now readily decomposed and easily crumbles into sand, and did so, apparently, quite as easily at the time the Old Red Sandstone was deposited upon it."

Further north into county Carlow, the sandstone gradually thins out and allows the limestone to rest directly on the surface of the granite. The beds of limestone dip gently from the granite, but are not altered by it, and were evidently deposited in the sea upon a bare floor of granite, just as beds might now be deposited upon it if the country were again depressed beneath the sea.[2]

2. *Somersetshire.*—The relative position of the newer and older rocks round the Bristol coal-field furnishes another excellent instance of unconformity. The older series, con-

[1] The relations of this granite to the surrounding rocks will be described in Chapter XI.

[2] Condensed from the account given in Jukes' "Manual of Geology."

sisting of the Devonian Rocks, Carboniferous limestone, and Coal-measures, are thrown into a broad periclinal basin, the uppermost series of coal-measures lying in the centre of this basin (see fig. 124); but these older rocks are unconformably overlaid by a much newer series, consisting of red sandstones and marls (Trias), dark clays (Lias), and oolitic limestone (Inferior Oolite), which lie nearly horizontally, and are spread over the edges of the carboniferous series, so as to conceal their outcrops in the manner indicated in fig. 124.

The figure is a generalized section through that part of the coal-field which lies to the N.E. of Bristol, and the faults which traverse the older rocks are not there very numerous or important; in other parts of the district there are a number of faults which break the continuity of

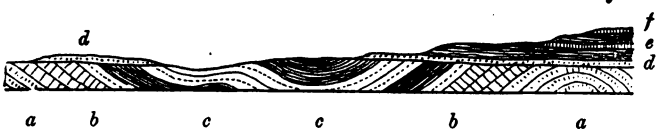

Fig. 124. Section across the Bristol Coal-field.

a, Devonian Rocks. *b*, Carboniferous Limestone. *c*, Coal-measures. *d*, Trias. *e*, Lias. *f*, Oolite.

the older strata, but do not extend through the newer rocks. Hence it is evident that the older series had been bent into folds and basins, fractured by faulting, worn down and denuded by detritive agencies, and finally planed down to a tolerably level surface by marine erosion, before the deposition of the newer series of deposits.

Lastly, these newer beds have themselves been exposed to great detrition, which has removed every vestige of them from many parts of the district, so as to lay bare the older series on which they repose. Sir A. Ramsay has calculated that the thickness of rock thus removed from the surface of the Mendip Hills during the two periods of erosion amounts to nearly one mile (5,280 feet).

Overlap may be described in this chapter, because the fact of overlap necessarily involves the existence of an unconformity. The term itself, however, does not denote any relation of a newer series to an older, but applies merely to

the relative extension of beds in a conformable series. Overlap occurs in a conformable series when each succeeding bed stretches beyond the limits of that below it in one or more directions, so as to have a wider extension, and to conceal the edges of the lower beds.

In fig. 125, it will be seen that the upper series of beds, marked C, L, have a continually increasing extension, and were formed during the gradual and continual submergence of the old land surface upon which they rest. It is also clearly seen that the overlapping beds are conformable to one another, though unconformable as a series to the rocks below. Overlap is indeed a necessary consequence of the underlying surface of denudation being an inclined plane instead of a horizontal one, consequently any slope in an area of subsidence will give rise to the phenomena of overlap.

Instances of Overlap.—One instance of overlap has already been mentioned as occurring in county Carlow, where the carboniferous limestone overlaps the old red sandstone. In other parts of Ireland, the coal-measures in like manner overlap the carboniferous limestone, and rest upon older rocks. An excellent example of both these overlaps is presented by the structure of the county of Dublin.

The rock-groups which occur in this county form two distinct series or systems—an upper and a lower,—the granite being included with the latter, because it was intruded into those rocks before the deposition of the upper series:—

Lower Series.	Silurian, Cambrian, Granite.	Upper Series.	Coal measures, Carboniferous limestone, Old red sandstone.

If the reader will refer to sheets 102 and 112 of the "Geological Survey of Ireland," where the surface exposures of the different rock-groups are indicated by different colours, and to the section, fig. 125, he will see that the beds of the upper series, taken as a whole, rest in different places on different parts of the lower series, and upon the granite. The upper rocks, therefore, are completely un-

conformable to the lower. These lower rocks rise to the surface in four separate localities—1, in the hills south of Dublin; 2, at the hill of Howth; 3, on the coast near Portraine, with which the island of Lambay was doubtless once connected; 4, in the district west of Skerries.

The next thing that would strike us is that, although there are so many miles of boundary to the rocks of the upper series, yet the basement beds of that series—viz., the Old Red Sandstone and the limestone shale—are only found at one locality, and that near the centre of the district (Portraine). No evidence of the existence of these basement beds was discovered, either along the southern or the northern border of the great limestone tract.

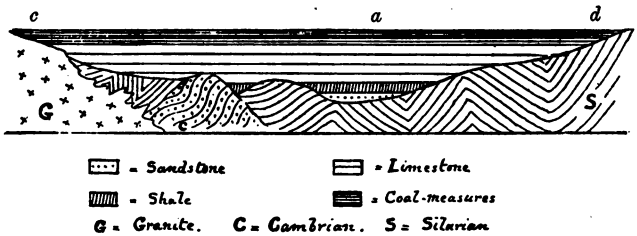

Fig. 125.

All these facts are only explicable on the principle of overlap in the following way:—Before the deposition of the upper series, the lower group must have formed an extensive area of dry land, with a widely denuded and irregular surface, as suggested in fig. 125, which was produced in the same way as such surfaces are now produced, viz., by the action of rain and rivers.

Eventually a movement of depression set in, and this dry land was gradually submerged beneath the neighbouring sea. The first portion of the area which was brought below the level of the water was the part about Portraine (below *a*, in fig. 125), either because it was depressed more rapidly, or because it was lower than the other parts of the country. Certain beds of sand, now forming the Old Red Sandstone of that locality, were accumulated there, and certain beds of black shale, forming the lower limestone shale, were deposited over them as the depression con-

tinued. These beds did not extend far to the north or south of that locality, simply because the water ended against the shore, within a short distance of it. As the land, however, continued to sink, the water extended farther and farther over it; and the beds deposited in that water acquired, in like manner, a wider and wider extension, and altogether overlapped those beneath them, as represented in fig. 125. It is probable that, as a final result, horizontal beds of coal-measures were spread over the whole area, resting upon the granite of the Wicklow hills on the south, and upon the Silurian hills of Meath on the north, and completely concealing all the limestone below. Patches of these coal-measures are only now to be found in the northern part of the district, having been removed from all other parts by the detrition which has produced the present denuded surface.

After all the beds were laid down in the manner indicated, a movement of elevation took place with its concomitant results of tilting, contortion, and fracture. The formation of a second land-surface, with its resultant denudation, brought to light the lower beds in different places according to circumstances, and re-exposed portions of that still older land-surface which had been covered up by the deposition of the carboniferous rocks.

The descriptions now given, when studied in connection with figs. 109, 122, 123, afford several instructive conclusions, illustrative of the principles formulated in these chapters :—

1. That the ancient (Palæozoic) rocks, consisting here of Cambrian and Silurian, with included Granite, were altered and contorted, denuded and planed down, so as to have a surface formed across their edges, before the deposition of the newer series.

2. That upon the surface so formed the sandstones forming the base of the Carboniferous system were deposited evenly and horizontally, and were followed by the Carboniferous limestone and Coal-measures in parallel or *conformable* succession.

3. That the total thickness of this upper, or Carboniferous, series amounted in Tipperary to at least 5,000 feet, which amount may be taken as a minimum measure of the extent of the depression which took place.

4. That the higher portions of the old land remained for some time as islands, but were eventually submerged, and that the successive beds of the carboniferous series overlapped one another against their slopes.

5. That at some subsequent period all these rocks were elevated, tilted, and faulted, the dislocation along one line of fault amounting to more than 4,000 feet (see p. 363).

6. That the country was again raised above the sea level, and underwent great denudation, from the action both of marine and terrestrial agencies, so as to lay bare part of the older land surface which had been covered up by the carboniferous series of rocks.

It is not always that the fact of overlap can be so easily detected, and the relative age and superposition of the overlapping beds so easily ascertained. Let us suppose that circumstances had been favourable for the formation of sandstones over the whole surface of the sinking land, and not only at one locality: sand and shingle beaches might have been formed continuously along the sea margin as the land sank, as the coasts receded, and as the sea gradually spread over a wider area. If this had happened, sandstones and conglomerates would be found resting on the old rocks under the points *c*, *d*, as well as under *a*, they would pass laterally into shale and limestone in the manner indicated previously on p. 308, and they would also be succeeded vertically by shale and limestone as the submergence became deeper and deeper. Such cases frequently occur, and are liable to lead the observer astray, unless he bear in mind that the sandstones, &c., which might exist under the points, *c* and *d*, would not be continuous and coeval with those under *a*, but were contemporaneous with the formation of pure limestone in the central part of the area. The first-formed beds under *a* would be the true basement beds of the series, but the last-formed beds would belong to the upper portion of the series, and would have to be considered as part of the coal-measures. If, however, the whole series subsequently came to be elevated again into land, tilted, contorted, fractured, and denuded, geologists who were not on their guard might easily suppose a succession of sandstones, shales, and limestones occurring always in the same order, and with similar characters, and belonging certainly

to the same system of beds, to be separate parts of one identical series.

Another good instance of overlap is to be found in the south-west of England, where the lower members of the Cretaceous series are successively overlapped by the upper members, as traced from east to west. The several groups of which this series is composed in the Isle of Wight have already been mentioned (see p. 334), and they are all to be found near Swanage, on the coast of Dorset, but when traced westward through this county by means of the sections exposed in the numerous coves described on p. 122, the Wealden beds become thinner and thinner, and are ultimately overlapped by the Lower greensand. Further west this, in its turn, disappears, and allows the attenuated representative of the Gault to rest directly on the Lias clays below near Lyme Regis. Beyond this point the Gault itself cannot be traced, for it becomes sandy, and is indistinguishable from the Upper greensand which continues

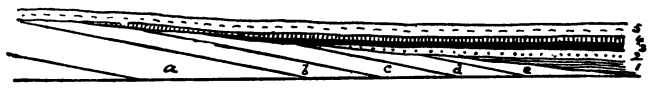

Fig. 126. Overlap and Overstep.

a b c d e = Jurassic Rocks. 1, Wealden. 2, Lower greensand. 3, Gault. 4, Upper greensand. 5, Chalk.

below the Chalk as far as the latter is traceable. This combined thinning out and overlap of the cretaceous beds may be represented diagrammatically, as in fig. 126.

Overstep or Transgression.—This should be distinguished from overlap because it is a relation between two rock-groups which are in unconformable succession; overlap being a relation between two groups which are in conformable succession. Overstep may be defined as the transgression or continuous extension of a single bed, or group of beds, across the outcrops of an older series of beds. It occurs when the older series has been tilted, so as to dip steadily in one direction before the deposition of the newer group. It is, therefore, a case of unconformity, and may or may not be accompanied by overlap.

One of the best instances of simple overstep in England

is the transgression of the chalk across the members of the Oolitic series in Yorkshire.[1] Another is that shown in fig. 126, where the newer series as a whole overstep successively the members of the older series: here it is accompanied by overlap, and the difference between the two phenomena is easily seen.

Practical Importance of the Subject.—The phenomena of Unconformity and Overlap, and the conclusions to which they lead us, have their practical as well as their theoretical interest; and the whole subject ought especially to be thoroughly understood by those who are engaged in searching for minerals which occur in one set of rocks, and can only be reached by boring through beds belonging to another set. The success of such borings depends in many cases upon the conformity or unconformity of the two sets of rocks; and the probable thickness of the upper set may be miscalculated unless the possible existence of overlap is taken into account.

Thus in county Antrim, where the Trias or New Red Sandstone rests on the Carboniferous rocks, there has long been a feeling that it is only necessary to sink through the sandstones in order to find the coal-measures. Since, however, the one lies unconformably upon the other, it follows that though in one locality the Trias may rest upon coal-measures, in other places it may lie upon any of the beds which come out from beneath the coal-measures; and from the structure of the district it appears that the chances are something like twenty to one against the coal-measures being found under any particular spot of the Trias.

The same is the case in the central districts of England, where the Coal-measures rest unconformably upon Silurian rocks, and are themselves unconformably overlaid by newer deposits of sandstone and conglomerate. Explorations in search of coal are from time to time undertaken in this district, and it is of the highest practical importance that the explorers should have a complete comprehension of the nature of these discordances, and of the possible consequences which they involve. Such knowledge is indeed absolutely necessary to avoid the fruitless expenditure of

[1] See "Geol. Mag.," Dec. 2, vol. x., pp. 224, 332.

large sums of money. Many thousands of pounds have been thrown away, in this central part of England alone, in abortive attempts to discover coal, the expenditure of which nothing but the most complete ignorance of geology could have rendered possible.

Again, in the Somersetshire coal-field (fig. 124), which is so largely covered by newer deposits that rest unconformably upon the older rocks, although coal has been worked in many places beneath the Triassic sandstones, it does not by any means follow that coal-seams will always be found below these sandstones. If a boring were made at the foot of the Cotteswold hills in the expectation of finding coal, the undertaking would in all probability prove fruitless; the bore would pass through the lias clays and Triassic sandstones, and would then enter either the Carboniferous limestone, or the still older rocks below it, as indicated in fig. 124.

It will be noticed, however, that in this figure an anticlinal axis is represented beneath the Cotteswold hills; this is hypothetical, but is considered to be a very probable occurrence, so that still further east the coal-measures may roll in again and form another basin beneath the newer rocks. As a matter of fact the coal-measures have been reached at a depth of about 1,000 feet below the surface at Burford in Oxfordshire, and it is quite possible that several such buried coal-fields may exist under the country between Bristol and London.

Recent borings in London, and at other places in Middlesex and Hertfordshire, have shown that the newer beds (chalk, &c.) rest unconformably upon a broad ridge of older rocks, comprising the Silurian, Devonian, and Carboniferous series, which appear to have a general dip to the south, and that by this southerly dip coal-measures which overlie the carboniferous limestone may be brought in to the south of London, and may underlie parts of Surrey.

The considerations above mentioned will be sufficient to demonstrate the great practical importance of an unconformity between two series of rocks.

CHAPTER X.

PETROLOGY OF IGNEOUS ROCKS.

IN the previous chapters we have examined the petrology of the Derivative or Aqueous rocks, we have now to deal with that of the Igneous rocks; viewing them as rock-masses which enter into the structure of the earth's crust. The different kinds of igneous rocks have been described in Chap. III.; and an outline of the phenomena exhibited by volcanoes was given in Part I., Chap. II.

It was stated on p. 104 that modern volcanic cones, in common with all other terrestrial surfaces, are wasted by rain and frost, so that their flanks are trenched by deep gullies and ravines. As long as the volcano continues to be active, these losses are more than counterbalanced by fresh ejections, but when volcanic activity finally ceases it evident that such losses cannot any longer be made good; the mountainous pile of ashes and lava-flows will slowly succumb to the continued action of the detritive agencies until nothing but a worn-down stump is left to mark the existence of the former volcanic cone. So long, however, as the district is not submerged beneath the sea-waves, some remnants of the old volcano will generally survive, and the existence of such extinct volcanoes in various stages of ruin and decay has already been mentioned.

If, however, the terrestrial surface upon which the volcanic cone was reared comes eventually to be submerged, the erosion of the sea-waves will effect a still more complete destruction, for they generally succeed in sweeping away all traces of the cone itself, and leave only the central pipe or chimney and the lava-filled fissures which formed the feeders of the old volcano.

These, however, are not the only relics of former volcanic action; lava streams have from time to time been poured

into the neighbouring seas and lakes, and have become interstratified with the deposits accumulated therein; again, some of the fragmentary materials are preserved in the same way, and form stratified layers of volcanic ash. Moreover, when eruptions have taken place beneath the sea, it is obvious that all the volcanic products must have been strewed over its bottom, and will be interbedded with the marine deposits of the surrounding area.

Viewed, therefore, as rock-masses and with regard to their mode of occurrence among other rocks, volcanic products always stand to these in one of two relations:—they are either injected or intruded through previously existing strata, or else they are interbedded with contemporaneous deposits. In a petrological description of these rocks it is then convenient to arrange them in two divisions under the respective heads of *Intrusive*, and *Interbedded* or *Contemporaneous*; but at the same time it must be remembered that these are only relative terms, and that the lava streams which issued from a submarine volcano, and were interbedded with the deposits of the surrounding sea, may have been directly continuous with the intrusive masses that remained in the vent and subterranean fissures.

In dealing with volcanic rocks and their mode of occurrence, it seems then most natural and convenient to proceed from the known to the less known. Commencing with the description of the remains of actual volcanic orifices which can be interpreted by our knowledge of recent volcanoes, we may proceed to consider the interbedded and intrusive masses which were once connected with such vents, but which differ so much in their mode of occurrence.

Class I. Contemporaneous Igneous Rocks.

A. *Remains of Ancient Volcanoes.*

Extinct Volcanoes occur in all parts of the world and in all stages of ruin and decay. Some still preserve their cones and craters, and the lava-streams proceeding from them are still rough and bristling, though they have never been active during historic times; others have had their

cones and craters more or less obliterated by the action of rain and frost, and the country around them has been so lowered by general detrition, and so altered by the erosion of valleys that the lava-streams which originally ran down the lowest ground they could find, are now found in detached remnants on the top of ridges and plateaux.

No better example of such extinct volcanoes could be cited than those of Auvergne, in central France, some of which are shown in the plate at the end of this volume.[1]

The Limagne d'Auvergne may be described as an extensive plain, chequered with low hills of fresh-water marl and limestone which are capped with portions of lava-flows (Plate, fig. III.). This tract is enclosed on the east and west by two parallel ranges of granite and gneiss, that to the westward forming a lofty plateau of granite, rising to a height of about 3,000 feet above the sea, and 1,600 above the valley of Clermont. This plateau supports a chain of volcanic cones and dome-shaped hills (Plate, fig. II.), about seventy in number, varying in altitude from 500 to 1,000 feet above the plateau and forming an irregular range nearly 20 miles in length and about 2 in breadth. The highest point of this range is the Puy de Dome, which rises to a height of 4,000 feet. Many of the cones retain the form of well-defined craters, and their lava currents may be traced as regularly as those of Vesuvius. Fig. II. is a view of part of the southern chain of Puys, as these hills are locally termed; several of them are broken down on one side and lava currents have issued from the gap.

One of the most remarkable cones is the Puy de Come, which rises from the plain to the height of 900 feet; its sides are covered with trees, and its summit presents two craters, one of which is 250 feet in depth. A stream of lava has issued from its base, but at a short distance, having been obstructed by a mass of granite, it has branched and flowed round it; thence it can be traced along the granitic platform and down the side of a hill into an adjacent valley, where it has dispossessed a river

[1] The following description of the volcanoes of Auvergne is abridged from that in Mantell's "Wonders of Geology," and founded upon Mr. P. Scrope's work on the "Geology of Central France."

of its bed, and constrained it to work out a fresh channel between the lava and the granite of the opposite bank.

Mont Dore (Plate, fig. I.) is a mountainous tract, the highest portion of which is about 6,000 feet in altitude. The dotted outline in fig. I. shows the presumed form of the crater when in activity, but the crater is ruined and broken down, and consists of a group of seven or eight rocky summits, which form a zone about a mile in diameter. The mountain is deeply channelled by two principal valleys, and is furrowed by many minor water-courses, all originating near the central eminence and diverging toward every point of the horizon. The whole mass consists of beds of scoria, tuff, trachyte, and basalt, all dipping from the central axis and lying parallel to the sloping flanks of the mountain, as in modern volcanoes.

Ancient Vents or Necks.—The actual site of an old volcanic vent is sometimes manifested, even after the total destruction of the cone itself, by the exposure of the cylindrical pipe which once terminated upwards in the central orifice or crater of the volcano. This pipe or chimney, when disclosed by denudation, is called a *neck*, and is always filled with some kind of volcanic rock, either by a plug of solidified lava, or by a mass of volcanic agglomerate. Such necks vary in diameter from a few yards to several hundred feet.

A vertical section of a neck filled with crystalline rock might be mistaken for a dyke, but a horizontal plan or surface exposure would show that it is a round or oval pipe and not a long fissure. In the case of agglomerate necks, the nature of the infilling material would prevent such a mistake being made. In most cases the surrounding rocks are partially baked or fused like those in contact with all other intrusive masses, but there is one class of necks in the neighbourhood of which no such alteration has taken place.

When a volcano has been worn down by atmospheric and marine erosion, till only the central neck or funnel, with perhaps some of the basal tuffs and agglomerates, of the old volcano remained, and the whole has been buried deep beneath subsequent accumulations, it will be entirely concealed from view within the earth's crust, unless the

whole tract has been again upheaved and exposed by still later denudation.

It must, of course, participate in all the movements and disturbances to which that portion of the earth's crust may be subjected; it may be tilted so that the inclination of the stratified tuffs is altogether altered, it may be broken and displaced by faults, and its lavas may be more or less metamorphosed. When the region is again uplifted, eroded, and denuded, the old volcanic vents may be exposed as necks descending more or less vertically downwards, as indicated in fig. 127; here *a* are the old rocks, which were rent by volcanic action, and pierced by the two columns of lava, *c* and *d*; these columns once terminated in volcanoes, of which only the basal portions now remain;

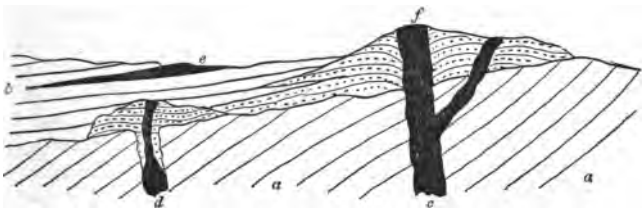

Fig. 127. Diagram to show the manner in which Volcanic Necks may be concealed and exposed.

b are the newer rocks with which some of the volcanic products were inter-stratified, and *e* is part of an interbedded lava stream, which originally proceeded from the vent that surrounded the neck, *f*.

There are several districts in the British Isles where numerous volcanic necks exist, and where they have been so dissected and laid open by coast erosion that their relations to the surrounding rocks can be examined in detail. County Antrim, in Ireland, and the shores of the Firth of Forth in Scotland, are two of these localities.

Fig. 128 is a sketch of a small neck of porphyrite in Haddingtonshire, as exposed on the shore, near the mouth of the river Tyne.[1] The beds of sandstone through which

[1] "Geology of East Lothian," p. 40.

it is drilled are baked and hardened, and it will be noticed that they are bent down so as to dip everywhere towards the central plug of lava. This inward dip of the strata surrounding a neck is of frequent occurrence, and may be attributed partly to the downward drag of the column of lava caused by its contraction during the process of solidification; the weight of the ejected materials above may also have helped to depress the subjacent strata.

Between the towns of Elie and St. Monace, on the coast of Fife, a magnificent exhibition of volcanic necks and dykes is to be found between high and low water mark. Close to St. Monace there is a large boss of volcanic agglomerate, with a plug of basalt in the centre, from which numerous dykes of green-coloured basalt proceed in various directions. Westward of this, and also exposed in plan, is a small neck filled with basalt, where the mutual

Fig. 128.

effects of igneous and sedimentary rocks in contact are beautifully shown, the shales outside being disturbed and porcellanized, while the basalt is bordered by a band of white trap from 2 to 3 feet thick. Still farther westward are several other examples of small necks filled with agglomerate, and projecting through the shales and sandstones which form the shore, so that the observer standing in the centre of one of them can easily take in the whole of its circumference. These must have been mere pocket-editions of volcanoes, and were probably only blowholes of dust and stones, for the shales in contact with the agglomerate are not altered like those around the basalt necks.

The alteration of the stratified rocks in contact with necks now filled with agglomerate, must have been effected by the previous passage of molten lava through the pipe, for it is evident that the passage of hot gases, dust, and stones could hardly produce much effect on its walls. It

can sometimes be demonstrated that this was the case, as in the following instance occurring in Ayrshire, and described by Prof. J. Geikie.[1] "Outside the volcanic ring (of interbedded ashes and lavas) there occurs a number of small rounded hills or hillocks consisting of a coarse red volcanic agglomerate. These hills are true volcanic 'necks,' each representing a former crater or focus of eruption. . . . They descend vertically through the Coal-measures like so many huge pipes, sometimes standing on lines of fault, while the coal near them is altered. In one case, that of Helenton Hill, near Monkton, I found the sides of the neck still partially crusted with a mass of rough scoriaceous melaphyre—the remnant of the slaggy scoria which once coated the walls of the volcanic orifice."

The Fifeshire examples, and others where the walls of the neck consist of unaltered stratified rock, are probably orifices which never gave exit to streams of lava, being merely holes blown out of the rocks by the force of gaseous explosions. They seem to find a parallel in the extinct volcanoes of the Eifel, of which Sir Charles Lyell says,[2] "The most striking peculiarity of a great many of the craters above described is the absence of any signs of alteration or torrefaction in their walls, when these are composed of regular strata of ancient sandstone and shale. . . . . There is indeed no feature in the Eifel volcanoes more worthy of note than the proofs they afford of very copious aeriform discharges, unaccompanied by the pouring out of any melted matter, except here and there in very insignificant volume."

B. *Interbedded Sheets.*

These consist of the coulées or lava-streams, and the ashes or tuffs which have been ejected from ancient volcanoes on to the bottoms of those seas or lakes which existed at the time when such eruptions took place. Covered up by the deposits subsequently accumulated, they now appear as interbedded between the beds upon which they were spread out, and those by which they were overlaid. Their very nature

[1] "Geol. Mag." vol. iii. p. 246.
[2] "Elements of Geology," eighth edition, p. 674.

and mode of origin, therefore, limits them to this one form or mode of occurrence, and all such interstratified masses may consequently be described as *sheets*. Further, it is evident that they and the sedimentary beds with which they are associated must constitute one consecutive series, and that in this sense the sheets of igneous rock are contemporaneous with the beds of stratified rock.

Proofs of Interbedding.—It is particularly important that the observer should be able to decide whether any sheet of igneous rock he may meet with is interbedded or intrusive; whether, in fact, it is to be regarded as contemporaneous with the rocks among which it lies, or as having been intruded between them at some subsequent time, for upon this determination depends the geological date which is assigned to the rock in question. It will therefore be desirable in the first place to examine the signs and circumstances which serve to distinguish interbedded from intrusive sheets of lava or trap. These are,

1. The slaggy or vesicular character of the upper and lower surfaces of the sheet.

2. The unaltered character of the overlying beds and their general relations to the surface on which they rest.

3. The association of stratified ashes or tuffs.

1. In the description of lava-streams given on p. 26, it was stated that their upper surface or crust was sometimes rendered slaggy and ropy by the motion of the current, and in other cases it became vesicular and scoriaceous from the escape of the contained gases. The surface of all lava-streams presents one of these two conditions in a greater or less degree, but intrusive sheets which have solidified under the pressure of the overlying beds do not exhibit these appearances. The under surface of a lava-stream is also very frequently full of vesicles, so that it is then vesicular both at the top and bottom; subsequent infiltrations may convert these vesicles into amygdaloids, but this only renders them more conspicuous. The cavities are often drawn out and elongated in the direction of the flow, so that by this means it is sometimes possible to ascertain the direction from which the amygdaloidal rock has come.

2. It is obvious that the beds overlying a contemporaneous sheet cannot be altered by it, because they were

not there when the rock was poured out as a stream of lava. An interbedded sheet, therefore, only alters and bakes the beds below, while an intrusive sheet affects those above as well as those below. The absence or presence of intrusive tongues or veins proceeding from the sheet is likewise a criterion, their presence at once indicating its intrusive nature. Farther, the stratification of the beds overlying an interbedded sheet generally affords evidence of their having been deposited upon the irregular surface of the trap, as indicated in fig. 129. The stratified rock fills up any hollows or cracks which may exist in its surface, and often encloses small pebbles or blocks which have been broken off from it.

3. The presence of stratified tuffs also raises the presumption that the associated sheets of lava are interbedded and contemporaneous, though it does not absolutely prove

Fig. 129.

this to be the case, for as we have seen, masses of tuff and agglomerate frequently fill up volcanic necks, and are then associated with the intrusive dykes which proceed from it. Still, if the sheets of trap are clearly interstratified with beds of "ash," and if the ash-beds do not exhibit any signs of baking or alteration where they are in contact with the lava, then it becomes almost certain that the trap is contemporaneous; for the chances would be greatly against a sheet of lava being injected into those ashes without producing in them great and obvious alteration.

Consecutive Flows.—Occasionally a single flow or sheet of trap is met with, and sometimes several such single flows are interbedded with a series of stratified rocks; more frequently, however, what appears to be one massive sheet is in reality made up of several distinct lava-flows poured out at separate intervals from the volcanic vent. The independence of the flows is sometimes indicated by diffe-

rences of texture, one being compact, another porphyritic, another columnar, and so on; even when all are similar in character, there are sometimes zones of vesicular or amygdaloidal rock, formed by the union of the upper and lower surfaces of two flows, which mark the lines of division between them. Lastly, the fact that such a mass is really made up of successive flows is often clearly demonstrated, when their outcrops are traced for some distance, by the intercalation of other beds between some of the component sheets. Such an occurrence proves that the lava currents invaded an area where deposition was going on, and that sufficient time elapsed for material to be deposited on the surface of the first sheet before it was overflowed by the second.

An excellent instance in which consecutive flows of doleritic lava are interstratified with shales and sandstones belonging to the Coal-measure series occurs in the Burrowstownness coalfield, Edinburgh. The middle part of this series is described as consisting of the following alternations of igneous and aqueous rocks:—

	Feet.
Shales and sandstones	—
Dolerite	20
Shale and sandstone	6
Dolerite in several sheets, with partings of shale and sandstone in places	265
Shale, coal, and sandstone	30
Dolerite in several sheets	110
Shales and sandstones	25
The "red coal" seam	3
Dolerite	4½
Sandstone	16

In one shaft the thickest compound mass of dolerite was found to be separated into two portions by the intercalation of 30 feet of shale and sandstone, thus:—[1]

	Feet.	
Dolerite in several sheets	150	318
Shale and sandstone	30	
Dolerite in several sheets	138	

[1] "Geology of Edinburgh, Mem. Geol. Survey," p. 63.

Such intercalations and alternations of lava-flows, ash-beds, and aqueous rocks are frequent wherever extensive eruptions have taken place, and the whole groups of strata thus formed have, of course, partaken in all the accidents of tilting, flexure, and fracture, by which the district has been affected since the time of their formation. The scene of such volcanic eruptions generally forms hilly ground at the present day, not because any relics of the old volcanic hills still remain, but because the hard crystalline lavas have withstood the action of subsequent detritive agencies; they now stand up as bold ridges or mountainous masses simply in consequence of their durability and capacity for resistance during the process of differential detrition (see Part III., Chapter I.). Thus in Scotland, the Pentland, Ochil, and Sidlaw Hills, and in Wales, the Snowdon, Aran, and Arenig Hills, owe their existence, as hill ranges, to the massive sheets of felsite, porphyrite, &c., which are there interbedded with the stratified rocks; and even in less disturbed districts, where the beds are only gently inclined, the outcrops of contemporaneous lava-sheets form bold ridges and escarpments.

Instances of Interbedded Lavas and Ashes.—1. *Snowdon.* The volcanic products which make up the mass of the loftiest mountain in Britain have a total thickness of more than 3,000 feet, and consist of the following members:[1]—

	Feet.
Columnar felstone	200
Ashy beds	1,200
Porphyritic felstones	1,700

These huge sheets of felstone are composed of numerous independent flows, and the slaggy surfaces of these flows are sometimes as apparent as in recent lavas. There are no clear traces of the vents from which these eruptions proceeded, except that they are thickest round a certain centre and thin away in every direction, becoming intercalated with beds of shale and sandstone, and finally dying out altogether. A similar change is also observable in the ash-

[1] See Sir A. Ramsay's "Geology of North Wales, Mem. Geol. Survey."

beds, which near the volcanic centre are extremely hard and compact, and consist entirely of the débris of slaggy and scoriaceous lavas, so that they sometimes resemble the decomposed portions of the felstones; but as they are traced from the central area they become thinner, more regularly bedded, and more obviously mechanical, the ashy and cindery materials become mixed with an increasing proportion of sandy, clayey, or calcareous sediment, and they finally pass into pure sandstones, shales, or limestones.

The whole of these rocks are cut through and penetrated in different places by subsequently formed dykes, veins, and intrusive sheets of diorite, felsite, &c., altering and disturbing the interbedded series, and thus completing the complexity and confusion which the geologist has to unravel.[1]

2. *The Limerick Basin.* Ireland presents us with an example of interstratified aqueous and igneous rocks in county Limerick, which is perhaps more interesting, and even more instructive than North Wales or other mountainous regions, because it has been less disturbed and is much more easily examined. The aqueous rocks, too, are chiefly limestone, so that there is no difficulty in distinguishing them from those of igneous origin.

In the north-eastern part of Limerick, enclosed by the lofty ranges of the Keeper, Slievragh, Knockfeerina, and Galtee Hills, is a rich plain, the centre of which is diver-

[1] Not only were the rocks thus complex at their first formation, but they have been greatly upheaved and disturbed, thrown into many and complicated folds, and broken by many faults running in various directions, heaving and dislocating the rocks now one way, and now another, and with ever varying amounts, sometimes throwing them as much as three or four thousand feet from the level of the corresponding beds on the other side of the fault. In addition to this the country has been worn and eroded into valleys and glens, with precipitous cliffs and crags separated by more or less inaccessible ravines; and as the rocks are frequently disguised by partial decomposition, and concealed over wide intervening spaces by soil, by vegetation, or by superficial accumulations of gravel, clay, and sand, it will be readily understood that it is no easy or unlaborious task, though often a healthy and delightful one, to trace out all this complexity, to restore order to all this confusion, to delineate the outlines and positions of the rocks as they now are, and to reason back to their original state, and to the causes which produced them (Jukes).

sified by groups of less lofty, but often steep and rough-looking hills. These inner hills rise into craggy knolls some 600 or 700 feet high, while much of the country about them consists of alluvial flats not more than 100 feet above the sea. They consist chiefly of masses of porphyritic felstone, some red, others purple, and others of greenish or blackish colours which are probably dolerites and basalts; some portions are regularly and beautifully columnar, others are quite vesicular and scoriaceous; the latter portions generally forming definite layers between the bands of compact lava, and indicating the union of the upper and lower surfaces of different lava-streams. In many places the vesicles are filled with amygdaloids of calcite, zeolite, or quartz.

Associated with these lavas are large irregular deposits of ash, consisting of beds of coarse and fine-grained materials obviously derived from the lavas. Some of these beds are coarse conglomerates, containing rounded blocks of trap and limestone, some of which are as large as a man's head, and many as large as the fist. Others consist of small grains which vary in size from that of a pea down to pin-heads and less, arranged in very regular parallel laminæ, the coarse and fine layers often alternating in regular bands about half-an-inch in thickness. These ashes are generally either purple or dull green, and some of the green kinds become still more fine-grained, so that the particles are ultimately indistinguishable even by the lens, and the rock becomes a compact green stone like a rude porcelain.[1]

Some of the great masses of trap, 800 or 1,000 feet thick, are found, when followed along their strike, to split up and let in alternations of beds of ash and beds of limestone with beds of trap, showing that the greater uninterrupted masses of trap were in reality formed by successive flows of molten rock at the bottom of the sea, and that, where each of these flows terminated or became thin, accumulations of ash or limestone took place on the sea-bottom in the intervals between the outpouring of one flow and that of the next, so as to cause these interstratifications. Pallas

[1] See the Explanations of sheets 143, 144, 153, 154 of the Geological Survey of Ireland.

Hill is a conspicuous example of this occurrence. Instances are not wanting of intrusive dykes cutting through both aqueous and igneous rocks; but being, of course, more readily distinguishable when they traverse the aqueous than the igneous rocks.

It is very remarkable, that on the south of the trappean basin we get a line of five intrusive bosses of trap, that rise up through the lower limestone, and one at about the same distance north of the trap basin. These look like some of the volcanic foci from which the bedded traps were derived, the old roots, as it were, of the submarine lava flows, exposed to view by the denudation of the limestones and traps that once covered them. Other foci or irruptive masses are doubtless concealed beneath the existing beds of trap in the central parts of the basin.

Scotland.—The country which lies on either side of the Firth of Forth was anciently the scene of great volcanic activity. Arthur's Seat in Edinburgh and Largo Law in Fife are excellent instances of denuded volcanic piles, the numerous necks of Fifeshire have already been mentioned, and the behaviour of interbedded and intrusive sheets of lava can be studied in the cliff sections along the coast.[1] Most of these eruptions took place towards the end of the Carboniferous period, but evidence of an earlier series of volcanic explosions are to be found in the ranges of the Sidlaw, Ochil, and Pentland Hills. "All these prominent ridges," says Dr. A. Geikie,[2] "are formed mainly of volcanic materials belonging to the period of the Lower Old Red Sandstone. Their general characters—beds of lava (porphyrite, &c.), with sheets of tuff and interstratified sandstones, shales, and conglomerates—leave no doubt whatever as to their having been truly erupted to the surface during that geological period.

"In the Pentland Hills they cannot be less than 5,000 feet thick. In the region between Nithsdale and Clydesdale their depth has been estimated at about 4,000 feet, while in the Ochil Hills they are probably much thicker.

"Together with the rocks which flowed out at the surface

[1] Consult Dr. A. Geikie on the "Volcanic Rocks of the Basin of the Forth, Trans. Roy. Soc. Edin." xxix. p. 437.

[2] "Trans. Geol. Soc. Edin." vol. ii. pt. iii.

as lavas, we meet with veins and bosses which have been intruded into these rocks as well as into the associated sandstones. There can be little doubt that these intrusive masses in the Old Red Sandstone (quartz-porphyrites, and felstones) are of the same general date as the sheets of interbedded volcanic material in the same formation. In such bosses as Tinto, Quothquan, and other isolated hills in Lanarkshire, as well as in the Ochils and in Ayrshire, we probably see the true necks or lower portions of the volcanic funnels through which the lavas and tuffs were ejected."

Basaltic Plateaux.—It has long been assumed that all erupted basaltic sheets were remnants of lava-flows which had once been connected with true volcanic cones. Baron Richthofen had indeed pointed out so long ago as 1868, that on the Pacific slope of the Rocky Mountains there is evidence of the emission of vast floods of lava without the formation of cones and craters, and he stated his belief that these eruptions had proceeded from great fissures out of which the lava had poured in a continuous stream. This theory was energetically opposed by Mr. Poulett Scrope, who demonstrated that the extensive plateaux of basalt in Auvergne were only separated from the cones with which they had originally been connected in consequence of the great erosion to which that country had been subsequently exposed. He argued that the apparent isolation of other plateaux was merely owing to the total destruction of the volcanoes from which they had been emitted (see Plate, fig. III).

Subsequent observations, however, have confirmed the probability of Richthofen's views; the extent of these American lava-floods has been found to be enormous, and it is estimated that in the States of Oregon, Idaho, Nevada, and Northern California they cover an area of 200,000 square miles. The date of their emission is comparatively recent; they have been poured forth over the bottoms of the present valleys, and the only natural sections of them are those in the gorges or cañons which the present rivers have been able to erode out of the vast plain of basalt.

Dr. A. Geikie thus describes one of these enormous lava

fields[1]:—"We had been riding for two days over fields of basalt among the valleys, and [at last] emerged from the mountains upon the great sea of black lava which seems to stretch illimitably westwards. It was as if the great plain had been filled with molten rock which had kept its level, and wound in and out along the bays and promontories of the mountain slopes as a sheet of water would have done. . . . . I looked round in vain for any central cone from which this great sea of basalt could have flowed. It assuredly had not come from the adjacent mountains, which consisted of older and very different lavas round the worn flanks of which the basalt had eddied. . . . I became convinced that all volcanic phenomena are not to be explained by the ordinary conception of volcanoes, but that there is another and grander type of volcanic action where the molten rock has risen in many fissures, and has welled forth so as to flood the lower ground with successive horizontal sheets of basalt. Recent renewed examination of the basalt plateaux and associated dykes in the west of Scotland has assured me that this view of their origin and connection, which first suggested itself to my mind on the lava-plains of Idaho, furnishes the true key to their history."

Dr. Geikie suggests that the similar sheets and dykes of basalt which occur in the north of Ireland and west of Scotland, and the enormous dykes which are so frequent throughout Scotland and northern England, are all manifestations of a grand series of fissure eruptions comparable to those in North America, but belonging to an earlier geological period. In support of this conclusion he appeals to the wide extension and horizontality of the basalt sheets, the absence or paucity of interstratified tuffs, the want of any satisfactory evidence for the thickening and uprise of the basalt towards what might be supposed to be the vents of eruption, and finally their apparent connection with a series of lava-filled fissures, some of which are no less than 200 miles distant from them.

That portion of the great lava-flood which is isolated in the north-east of Ireland covers almost the whole of

[1] "Geological Sketches," by A. Geikie, p. 278.

county Antrim with a mass which is in some places 900 feet thick; it is 50 miles long by 30 wide, or about 1,200 square miles in area. The basalt mass consists of numerous sheets or flows, some of which are quite amorphous, either compact or amygdaloidal, while others are beautifully columnar; one of the columnar sheets dipping gradually into the sea on the north coast is known as the Giant's Causeway.

Similar extensive plateaux of basalt occur in other parts of the world, in Abyssinia, western India, and Victoria, and probably mark the sites of some of the great fissure-eruptions which have taken place at different times in the history of the world. In their recent résumé of the geology of India, Messrs. Blandford and Medlicott describe the persistent horizontality of the great basalt sheets which form the plateaux of the Deccan, the absence of any trace of associated volcanic cones, and the abundance of dykes which traverse the underlying platform of older rocks, where these emerge from beneath the basalt-covered area.

CHAPTER XI.

PETROLOGY OF IGNEOUS ROCKS (*continued*):

Class II. *Intrusive Rocks* (*Volcanic and Plutonic*).

We have now to consider the intrusive masses of igneous rock which occur in the earth's crust, those portions which have been injected either into vertical cracks, or between the layers of stratified rocks, or have as it were eaten their way upward, till they now appear as irregular masses, displacing or replacing a certain amount of stratified rock.

In the last chapter we dealt exclusively with *Volcanic* rocks, and had no occasion to mention those to which the name of *Plutonic* is often applied (see p. 273); those, namely, which have cooled slowly under great pressure, and at great depths. Although this distinction is of little value in the lithological description of rocks, it becomes of some use when we have to deal with the petrological relations of those which occur in the form of intrusive masses. Some of these are referable to the Volcanic division, and others to the Plutonic. For our present purpose, therefore, in order to describe all such masses of igneous rock as are intrusive among other rocks, we may regard them as belonging to one of the three following series:—

Volcanic.		Plutonic.
I.	II.	III.
1. Rhyolite.	Quartz-felsite.	Granite.
2. Dacite.	Quartz-porphyrite.	Tonalite.
3. Trachyte.	Felsite.	Syenite.
4. Andesite.	Porphyrite.	Diorite.
5. Basalt.	Dolerite.	Gabbro.

The *first* of these series consists of rocks that are essentially Volcanic; they are all close-grained, lava-form rocks

crystallized from a state of fusion (see p. 257), and only occur *intrusively* in the form of dykes, veins, and sheets.

The *third* series includes those rocks which are essentially Plutonic. They are all so coarse-grained that the term *granitoid* is sometimes applied to them collectively. They have crystallized from a state of fusion at great depths, and usually occur in the form of large irregular masses or bosses from which dykes and veins may or may not proceed.

The *second* series comprises rocks of an intermediate character, which sometimes occur in the massive form, and sometimes in the form of sheets or dykes.

The rocks which are placed on the same line form groups which have a natural connection with each other, so that we may expect to find rhyolitic lavas connected with dykes of quartz-felsite, and the latter proceeding from a mass of granite.

A. Volcanic Division.

Dykes and Veins.—A dyke is a wall-like mass of igneous rock which has been intruded along the line of a more or less vertical crack or fissure. Dykes have already been mentioned in Part I., Chapter II., but those described in that connection were chiefly the smaller dykes which intersect the volcanic cone itself, and not the more deep-seated dykes which traverse the underlying rocks. When such dykes are exposed to view by subsequent denudation, the baked or partially fused condition of the rocks which form the sides of the lava-filled fissure clearly indicate the igneous character of the intruded material. The extent to which the adjoining rocks are thus metamorphosed varies from a few inches to several feet; sandstones are changed into quartzite, shale is indurated or vitrified into hornstone, limestones are made compact and crystalline.

The intersection of stratified rocks by dykes of igneous rock is illustrated in fig. 130, which represents vertical dykes of basalt traversing nearly horizontal sandstones in the Isle of Skye; some of these dykes have decomposed and crumbled away, leaving vertical gaps or trenches in place of the igneous rock which originally occupied them.

The opposite coast of Ireland (county Antrim) is simi-

larly trenched in various directions by dykes of basalt, which are especially numerous in the country near Belfast. On the shores of the Lough they form straight causeways, standing up as vertical walls several feet high, exactly as if they were artificial quays. The slopes of Cave Hill are traversed by dykes, some of which can be traced up from the coast, and are seen in the chalk quarries forming vertical black seams which cut through the white limestone in a most picturesque manner. Some of these dykes are probably connected with the sheets of basalt on the hill-top, but others may not have succeeded in reaching the surface. They vary in width from 2 or 3 feet up to 20 or 30, and are traceable sometimes for several miles in straight lines, several adjacent dykes being parallel to each other.

Occasionally a dyke has been intruded along a line of

Fig. 130. Dykes at Straithaird, Isle of Skye.

fissure which is also a fault, as in fig. 131, where the basalt, *b*, occupies the space between the walls of a fault by which the coal-measures, *a*, *d*, are displaced to the amount of 90 yards. This instance occurs in the Dudley coal-field near Barrow Hill. The intrusion of the igneous rock has doubtless greatly widened the original fissure, for the present width of the dyke is about 140 yards. One of the most remarkable examples of a dyke is that known as the Cleveland dyke, which runs from the Yorkshire coast south of Whitby for a distance of about sixty miles in a north-west direction to Cockfield Fell in Durham. This dyke forms a nearly vertical wall of basalt 50 or 60 feet thick, cutting through all the other rocks which it meets with, and baking them for a distance of some yards from its sides.

We have no means of knowing how far such dykes ex-

tend downward into the earth, but if we could follow them far enough we should probably find that they proceeded from some large intrusive mass of diorite or syenite, and that they exhibited every gradation from the characters of a Volcanic to those of a Plutonic rock.

The smaller and more irregular intrusions, which proceed either from dykes or from intrusive bosses, are termed veins; these often pursue tortuous courses, and penetrate along any lines of weakness that may exist until they die away into mere strings and threads.

Intrusive Sheets.—When, instead of filling a more or less vertical fissure, the igneous rock has been intruded between the planes of stratification, it is called a sheet. Intrusive sheets of greenstone (probably diorite) have been

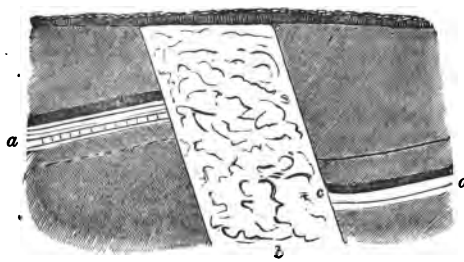

Fig. 131. Section of a dyke occupying a line of fault.

traced for miles in the rocks of North Wales, running regularly between two beds, as if they were interbedded with them, till at length they were found to cut obliquely up or down, and continue their course between other beds (see fig. 132); in such cases the rocks both above and below the sheet of trap will be baked and altered just in the same way as the rocks on each side of a vertical dyke. It often happens, too, that the upper and lower surfaces of the igneous rock or trap are likewise altered by the contact with the stratified rocks, especially if these are of a calcareous or carbonaceous nature; the trap loses its dark colour, assumes tints of pink and green, or even becomes quite white, and chemical analysis shows that such white traps contain from 9 to 10 per cent. of carbonic acid, and

10 or 11 per cent. of water. Thin sheets and horizontal veins are sometimes changed into a white pink or reddish trap throughout their whole thickness.

Excellent instances of such mutual metamorphism occur in Fifeshire, which has been the scene of extensive and repeated volcanic intrusions. The results of one of these intrusions may be studied on the shore at Ross End near Burntisland, where the calciferous sandstones are invaded by a sheet of dolerite. The sandstones are converted into quartzite, and all stages of alteration can be traced in the base of the dolerite, passing from dark green, through light green, to pink and white, and in one place it is

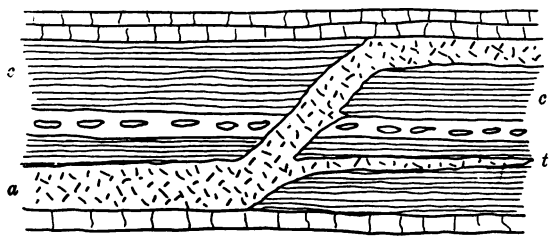

Fig. 132.

Sheet of igneous rock, *a b*, traversing shales, *c*, and sending off a tongue, *t*.

bright red, with amygdaloidal inclusions. The main sheet sends off intrusive branches and veins of white trap into the quartzite, fragments of which have been broken off and included in the igneous rock; these veins can be followed for many yards, and hand specimens may be obtained exhibiting the junction of the trap and the quartzite.

Similar instances are found in the South Staffordshire coal-field, as described by Mr. Jukes,[1] who specially mentions one in the Grace Mary colliery, where a part of the Tenyard coal and associated sandstone is penetrated by an irregular sheet of white earthy trap, which has, however,

[1] "Geology of S. Staffordshire Coal-field, Mem. Geol. Survey."

probably proceeded from the black basalt of the neighbouring Rowley Hills. The sandstone has not been much altered by the contact, but the coal has lost its bright lustre and much of its inflammable character.

The island of Skye has already been mentioned as exhibiting many examples of vertical dykes, and associated with these there are equally interesting and instructive cases of intruded sheets. Fig. 133 is copied from a sketch by Dr. Macculloch, and shows a large dyke-like mass of basalt, *a*, piercing the sandstones, *e*, and giving off a thick horizontal sheet, which splits up into three smaller sheets or veins (*c c c*); other dykes and veins run into or from this sheet, both upwards and downwards.

The extent and thickness of intrusive sheets is sometimes very considerable; thus in South Staffordshire a large sheet of dolerite, varying in thickness from 20 to 60 feet, was found to spread over an area of at least twenty

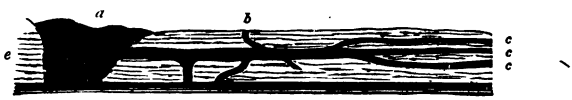

Fig. 133. Dyke and Sheet of Basalt, Trotternish, Skye.

square miles; in one part of the district it lies at a certain depth below the bottom coal, but in another part it passes upwards through that coal and spreads out over it, in some places even sending up dykes and protuberant bosses into still higher measures.

In such cases as these we may suppose that having been forced up through previously-formed fissures to a certain height, the molten rock then met with such resistance above, that it was as easy for it to lift the overlying beds as to break through them, see fig. 133. The planes of stratification would then become those of least resistance, and the molten stream would be injected along those which yielded the most readily, thinning and swelling out according to the varying pressures which were encountered in its course.

Laccolites.—The explanation just given leads us to the consideration of the still more massive intrusions,

forming huge lenticular masses of felspathic or trachytic rock, to which Mr. G. K. Gilbert has given the name of *laccolites*, or stone-cisterns. These appear to consist of the less fluid acidic lavas, which do not flow so rapidly (see p. 26), and would not be able to make their way between the planes of stratification so easily as the more fluid basaltic lavas. Such intrusions, therefore, would exercise still greater upward pressure, and could not fail to lift the overlying beds to a greater extent than the doleritic intrusions, while the accumulated weight will doubtless also depress the underlying rocks to some extent, see fig. 134. The intrusion will eventually take the form of a vast lenticular mass or reservoir of igneous rock. Some laccolites may have communicated with the surface, but those described by Mr. Gilbert in the Henry Mountains, Utah, do not appear

Fig. 134.
Diagram of a Laccolite.

to have done so. It is possible that the basic lavas may under certain circumstances be capable of forming similar laccolites. Thus, Mr. D. Forbes has suggested that the basalt of the Rowley Hills in Staffordshire was injected as an irregular lenticular mass between the Coal-measures, uplifting the superincumbent beds without reaching the surface, in the manner noticed in the eruption of Kilauea, recorded in Lyell's "Elements" (p. 617). The Rowley Hills are described by Mr. Jukes as formed by a capping of basalt 200 or 300 feet thick overlying the Coal-measures. "The thick coal," he says,[1] "has been worked round three sides of the hill, and it appears generally to dip under and pass beneath the basalt." Since his examination of the district, the Netherton Canal tunnel has been driven completely

[1] "Geology of South Staffordshire Coalfield," p. 119.

through the base of the hill from one side to the other, and underneath the mass of basalt; the only igneous rock cut through in this undertaking was a dyke not more than 8 feet wide, which appeared to be the only channel through which the overlying mass was extravasated. The weight of this mass of basalt seems to have been sufficient to weigh down the subjacent strata on every side, but the removal of the overlying beds renders it impossible to say for certain whether it behaved in other respects as a true laccolite.

Massive Intrusions or Bosses.—It has already been stated that igneous rocks sometimes occur in large irregular masses which take the place of so much stratified rock; these generally form rounded bosses or eminences in the midst of the surrounding rocks, which are generally

Fig. 135. Intrusive Mass of Dolerite at Barrow Hill, Dudley (after Murchison).

1. Dolerite. 2. Coal-measures. 3. Faults. 4. Altered coals, &c.

considerably baked and altered where they are in contact with the igneous rock.

The eminence called Barrow Hill, near Dudley, may be cited as an instance. This mass consists of coarse basalt or dolerite, and its surface exposure forms a pear-shaped area (as shown on the Geological Survey map), but below the surface it widens out in the manner suggested diagrammatically in fig. 135, sending out tongues into the adjoining coal-measures, which are much baked and charred.

As a rule, the rock of which such intrusive masses consist is more coarsely crystalline than when it appears in the form of dykes or sheets, the cause probably being that it has consolidated under much greater pressure, for it is often observable that the interior portions are much more largely crystalline than the outer parts of the mass.

An excellent instance of this came under the writer's notice at Dalmeny on the Firth of Forth, where the carboniferous shales and sandstones are interrupted by an irregularly oval mass of igneous rock more than a mile in width. Its outer portion is an ordinary fine-grained dolerite, but towards the interior the crystals of augite and felspar became very distinct, and the central portion is as coarsely crystalline as any granite, some of the augite crystals being an inch in length; scattered crystals of quartz and mica increase the granitoid aspect of the rock, which may perhaps be designated as an augitic gabbro.

Similar masses of dolerite, felsite, diorite, and porphyrite, &c., are to be found in different parts of the world, and their manner of occurrence leads us naturally to the consideration of those igneous rocks which never occur in any other way, but form massive intrusions often on a very large scale.

B. Plutonic Division.

Position of Granite.—Granite generally makes its appearance at the surface in large masses, occupying considerable areas, and extending for a great but unknown depth into the interior. Veins of granite, often branching and crossing each other (see fig. 136), usually proceed from these masses and penetrate the adjoining rocks; sometimes forming thick dykes or well-like masses which traverse these other rocks for great distances. Smaller bosses of granite are likewise not unfrequent in such districts, apparently the tops and eminences of larger masses which are still concealed below.

Granite generally forms high mountainous ground, the hills composed of it having commonly a heavy rounded outline and grey sombre aspect, while the surface is broken here and there by rounded knobs and bosses of bare rock.

Granite used frequently to be described as forming the axis of mountain chains, or the nucleus of mountain-masses, and it was taken for granted that the upheaval of the granite tilted and shouldered off the stratified rocks which rested upon it, so that these always dipped away from the granite; the lowest formation resting against it on each

side with a regular upward succession as we proceeded from it. The occasional appearance of granite masses in the centre of mountain chains favoured this view, but more careful and extended examination showed that the granite was exposed, not because it had been forced up to the surface, but because all the rocks under which it originally lay, and into which it was thrust, had been subsequently removed by the agents of detrition and denudation.

It is doubtless true that granite is more frequently associated with the older rocks than with the newer, in other words, with the lower than with the higher rocks, and hence the whole class of Plutonic rocks have sometimes been termed *Hypogenous*, or nether-formed rocks. The

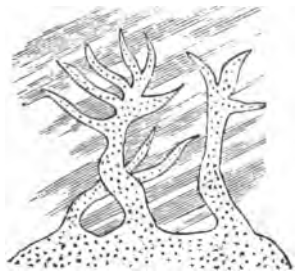

Fig. 136. Granite veins.

reason of this, however, is clear, from the very source of granite being in the interior of the earth; it must have passed through the lower rocks in order to reach the higher, and many injections of granite have only penetrated the lower rocks without proceeding further. That granite should generally be associated with rocks that have formerly been deep-seated follows, too, from its coarsely-crystalline texture. Molten rock that reached or came near the surface would not consolidate into granite, but would form quartz-felsite, rhyolite, or trachyte.

There is also a still more cogent reason why granite should occupy this position, viz., that all granite now found at the surface must be there in consequence of vast denudation having taken place, great masses of other rocks

having been removed by detrition, together, perhaps, with much of the granite that once existed above the present surface. This denudation of course exposes the lower rocks to view, while parts of the higher rocks that were perhaps equally penetrated by the granite have been removed, the other parts which remain being at a distance from the granite, and showing no signs of such penetration.

The relations of a large mass of granite to the adjoining rocks are generally rather complicated, the boundary line being very irregular, and the granite running out into tongues and bosses as already mentioned. Where the junction of granite with other rocks can be studied over a large area it suggests the arrangement exhibited in the diagram, fig. 137. The molten rock would seem to have forced its way upwards and sideways, eating away support after support of the mass above it, and probably in some cases actually melting them down and absorbing their materials into itself. The pressure from below has caused not only injections of the yet molten rock into the cracks and fissures of the superincumbent mass, but undulations in the general surface of the granite, some parts of the overlying mass being heaved up, and others sinking down into the granite. The upper surface of the granitic mass, on its final consolidation, would thus be an excessively irregular one, with protuberent mounds and deep hollows, while the beds of the superincumbent mass would not be likely to conform at all to this irregular surface, but would often dip directly down on to it, or abut against it in all kinds of ways, and with any amount of inclination.

Fig. 137 may be taken as a diagrammatic illustration of a tract of stratified rock invaded by granite, G representing a mass of granite gradually forced upward into the mass of slate, which had already been disturbed and tilted in various directions. The zigzag lines are intended to represent the extent to which metamorphism affected the slates in the neighbourhood of the granite. The horizontal lines, *a b*, *c d*, *e f*, &c., indicate successive surfaces of denudation. So long as the surface was represented by *a b*, no part of the granite would be seen, and little metamorphism would be observable. If the denudation reached to the surface, *c d*, some veins of granite would be visible, and these would

become more frequent along the surface *e f*; intermediate surfaces between *e f* and *g h* would expose thick bosses of granite with many patches of mica-schist upon, and apparently dipping down into it; the width of the granite area would be wide in proportion to the depth of the denudation, and when a large area was exposed, the veins would only be visible round its borders.

These ideas respecting the form of the original subterranean surface of granite masses are corroborated by an examination of the districts where large areas of granite are exposed.

Granite of Leinster.—The largest surface exposure of granite in the British Islands is that of the Leinster district; this granite area occupies large parts of the counties Wicklow, Carlow, and Wexford, being 70 miles long and

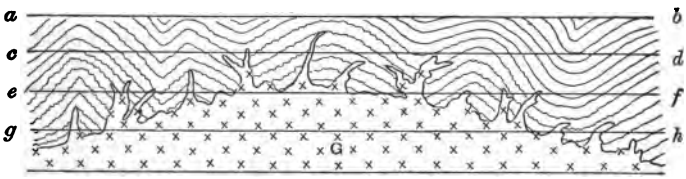

Fig. 137. Diagram to illustrate the intrusion of Granite (after Jukes).

from 7 to 17 miles wide. The rocks surrounding this area belong to two distinct formations, known respectively as the Cambrian and Silurian systems, the former being the lower and older. Each of these are several thousand feet thick, and their component beds are greatly bent and contorted. Now although we are compelled to suppose that the granite must have come through the Cambrian rocks before it could penetrate the Silurian, yet it is remarkable that in no instance does any part of the lower or Cambrian formation come in contact with the granite at the surface, though it does come in some places within two or three miles of it.

This, therefore, is a sufficient refutation of the old idea that the intrusion of granite was the cause of elevation, and that the rocks in contact with it were always the lowest

and oldest to be found in the country. In the Leinster district it is Silurian or newer rocks which are seen to be altered into gneiss and mica-schist by contact with the granite. "Moreover, in those parts where the granite forms lofty hills, the mica-schist spreads far up on the flank of those hills, and on the very loftiest, such as Lugnaquilla (which is over 3,000 feet above the sea), large patches of mica-schist occur even on the summit, so that the surface exposure of granite is there narrowest and most interrupted." Had the hills been left another 500 or 1,000 feet higher, the granite would apparently have been entirely concealed there by masses of mica-schist stretching completely over it.

"On the other hand, where the granite forms low ground, as above Tullow and Hacketstown, its surface exposure is there by far the widest, and all the central part of it is completely free from patches of mica-schist.

"It is obvious that these differences are the result of the different amount of denudation that has acted on the granite. Where the ground is loftiest we have the nearest approach to the original surface of the granite and its original covering of other rock; where the denudation has cut down deepest, so as to form low ground, there we get deeper into the granite mass, or further from its original surface, to a depth, indeed, to which no mass of mica-schist could extend, unless it were altogether detached from the overlying mass, and enclosed in the granite."[1]

It is therefore almost certain that the whole of Wicklow and Wexford is underlain by a continuous mass of granite with a very irregular surface.

Granite of Cornwall and Devon.—Similar conclusions could be drawn from the study of other districts. The granite exposures of Dartmoor, for instance, and the other masses which rise to the present surface in Devon and Cornwall, are probably only knobs or bosses projecting from a connected mass below. The Dartmoor granite penetrates and alters rocks belonging to two different systems, viz., the Carboniferous and Devonian. Its intrusion, however, has not everywhere brought up the

[1] Quoted from Jukes' "Manual of Geology," second edition p. 318.

lowest—viz., the Devonian—rocks to the surface; neither does it appear to have acted in any sense as a geological axis or centre of elevation, but cuts across the boundary line between the two sets of rocks, breaking through them in a large irregular mass, which rises into hills of considerable height and clearly occupies the place of so much stratified rock (see fig. 138).

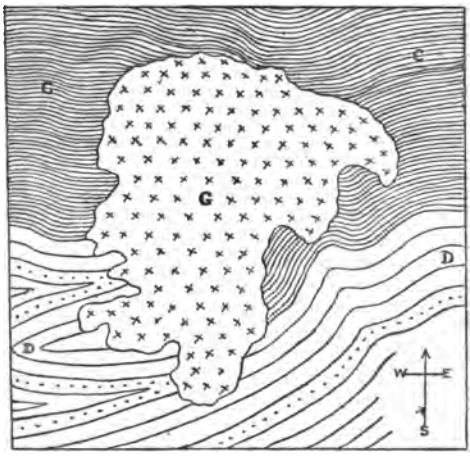

Fig. 138. Sketch Map of the Dartmoor Granite.
G = Granite. D = Devonian. C = Carboniferous.

On the north-east side of Dartmoor beds of volcanic ash and sheets of "greenstone" are interbedded with the shales and sandstones of the Carboniferous series; and these bands of contemporaneous volcanic rock are cut off by the granite, which is thus shown to be newer (as regards the date of its intrusion) than the period to which these older igneous rocks belong. Fig. 139 is a section across the granite on a smaller scale from north to south.

The metamorphic action of the granite upon the contiguous rocks does not generally extend to a greater distance than a quarter of a mile, but varies according to the relative fusibility of the rocks; and where the beds dip

off the granite, as they do on the north-east side, it extends farther.

The other granitic intrusions of Devon and Cornwall exhibit similar phenomena. There is absolutely no relation between the boundary lines of the granite bosses and the dip or strike of the slates into which they penetrate. On this point Mr. Jukes remarks: "The entire want of conformity between the irregular outline of the surface of the granite and the position of the aqueous and metamorphic slates about it has, I believe, been the origin of much scientific and some practical misapprehension. Mr. Curwen Salmon was kind enough to send me some time ago an instance of the latter from one of the Cornish mines, where, trusting to the apparent dip of the slates, a shaft was sunk

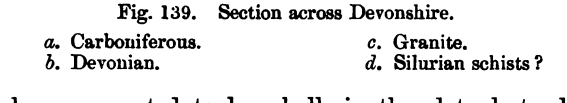

Fig. 139. Section across Devonshire.

a. Carboniferous.
b. Devonian.
c. Granite.
d. Silurian schists?

which was expected to be wholly in the slate, but which unexpectedly came down upon a subterranean mound of granite. The student will do well to recollect that it is quite possible for beds to dip directly at and into a mass of granite." [1]

Connection of Plutonic and Volcanic Rocks.—The granite masses above described appear to have consolidated beneath a great thickness of over-lying rock; and there is no evidence to show that any portions of them made their way upward through this rock, so as to be connected with volcanic phenomena at the surface. In other cases, however, it is more than probable that the granites are the basal reservoirs of ancient volcanoes, and the parent masses from which actual lava streams have proceeded.

The probability of this might be deduced from the similarity in the ultimate chemical composition of the granites, quartz-felsites, rhyolites, and obsidian, as shown by the

[1] Jukes' "Manual of Geology," third edition, p. 245.

following table of analyses, in which their mean composition is given:—

	Granite.	Q. Felsite.	Rhyolite.	Obsidian.
Silica	72·8	74·27	76·58	71·56
Alumina	15·3	13·12	12·25	13·80
Potash	6·4	4·44	3·10	3·46
Soda	1·4	2·48	4·55	5·54
Lime	0·7	1·17	0·86	1·44
Magnesia	0·9	0·52	0·38	0·47
Oxides of Iron and Manganese	1·7	2·43	1·70	2·09
Loss by Ignition	0·8	1·06	0·64	0·44
	100·0	99·50	100·16	98·78

Jukes remarked that "if we could follow any actual lava stream to its source within the bowels of the earth, we should in all probability be able to mark in its course every gradation from pumice or obsidian to actual granite."

Dr. A. Geikie has described the masses of granite, syenite, and quartz-felsite which rise to the surface at various places in the southern uplands of Scotland, and present many strong analogies to volcanic "necks." These bosses have a rounded or oval ground plan, and rise into dome-shaped hills or prominences; they pierce the stratified rocks, seriously interfering with the general dip and strike. Many of them are flanked by felspathic lavas and tuffs of contemporary date; and he therefore regards them as the stumps of some of the volcanic necks which supplied the melted and fragmental materials (see p. 405).

Dr. Geikie also suggested, and Professor Judd subsequently proved that the great dome-like masses of granite and syenite forming the central hills of the islands of Skye, Mull, and Arran, were the cores of old volcanoes. Professor Judd has shown that from these central masses intrusive spurs and dykes may be traced in various directions, which exhibit every variety of structure, from coarsely crystalline granite to the vitreous substance of lava; and further that these dykes are connected with lava-like sheets of rhyolite and trachyte, which occur round the flanks of the mountains.

In connection with these volcanic granites it is noticeable that the stratified rocks through which they have made their way never exhibit much local metamorphism. The igneous rock is never surrounded by a broad belt of metamorphic rocks like that round the Leinster granite. It would appear as if the heat and force, which would have been expended in metamorphic action below the surface, had been employed in producing the explosive phenomena of a volcanic vent.

There are similar grounds for connecting many masses of syenite, quartz-felsite, diorite, and gabbro with the sites of actual volcanoes, and with lava-like sheets of felsite, porphyrite, or dolerite. Professor Judd has shown in his excellent dissection of the ancient volcano of Mull,[1] that the early ejection of felspathic lavas connected with the core of granite was succeeded by an extrusion of basic lavas similarly connected with a great mass of gabbro. The granite core is rent asunder by the later intrusion of gabbro, from which proceed numerous dykes of dolerite, and these lead on to the vast sheets of basalt which surround the volcanic area.

Granite Veins and Elvans.—Similar conclusions may be deduced from a study of granite veins. The projecting bosses and veins which proceed from a granitic mass often differ considerably in lithological character from the deeper and more central portions of the parent mass. Sometimes they differ in mineral composition, and sometimes in their grain or texture.

Professor Haughton has shown that the Leinster granite in its central portions consists of four minerals, in the following proportions:—

Quartz	27·66
Orthoclase	52·94
White mica	14·18
Black mica	5·27
	100·05

But the composition of the outlying bosses which protrude

[1] "Quart. Journ. Geol. Soc." vol. xxx., and "Volcanoes," p. 142.

through the slate rocks outside the main chain he found to be very various—no two of them being exactly alike. The percentage of silica varied from 66·6 to 80·24, that of alumina from 11·24 to 18, while in the great majority of them the percentages of soda and lime were greater than those of the potash. These differences he attributes to the absorption and incorporation of portions of the surrounding slates into the granitic mass. In one of the detached bosses, that of the hill known as Croachin Kinshela, a specimen taken from the lowest part of the granite exposed showed a composition resembling that of the main chain, while another specimen from the summit of the hill nearer the original slaty envelope of the granitic mass, deviated greatly from it in composition, and contained chlorite instead of mica.[1]

Granite veins when traced from the parent mass frequently become more fine-grained, and eventually less crystalline and more earthy, commonly losing much of the mica, and often more or less of the quartz which they originally contained. Sometimes they take up into their constitution additional materials derived from the rock which they penetrate. An excellent instance of this is described by Professor Haughton, in the Mourne mountain district of north-east Ireland. He shows that near Carlingford there is a granitic tract about 5 miles in diameter, and that the composition of the main mass is as follows:—

Quartz	20·70
Orthoclase	66·37
Mica	12·76
	99·83

This granite sends veins into the overlying carboniferous limestone, and the contact of the two rocks—igneous and aqueous—has greatly altered the characters of both. The limestone is converted into a bluish sugary marble containing garnets, while the granite presents the following modifications:—(1) the normal granite passed into a syenitic or

[1] See "Quart. Journ. Geol. Soc." vol. xii. p. 171, and "Trans. Roy. Irish Acad." vol. xxiii. part 2.

hornblendic granite, and a piece taken about 10 yards from its contact with the limestone had the following composition:—

Quartz	17·16
Orthoclase	67·18
Hornblende	15·40
	99·74

(2) the veins proceeding from this hornblendic granite, and penetrating the limestone, passed into a kind of diorite or corsite consisting of—

Anorthite	85·84
Hornblende	14·16
	100·00

Comparing the last two rocks we see "that the quantity of hornblende remains almost unaltered, and that the effect of the addition of limestone to the melted granite has been to convert the quartz and orthoclase into anorthite. In this operation the alkalies of the orthoclase have disappeared; the lime being a more fixed base at high temperatures has altogether displaced the alkalies."[1] It may also be observed that the corsite contains 24 per cent. less silica than the hornblendic granite.

Veins of a compact felsitic character are sometimes to be found in the granite itself, and contrast strongly with the surrounding coarsely crystalline and highly micaceous rock. In some cases these veins seem to have been the result of a mere local difference in the aggregation of the minerals during the consolidation of the rock. Jukes observes that instances occur at Killiney, where, in veins about 3 feet wide, the general mass of the rock is ordinary coarse-grained, micaceous granite, "but parts of them suddenly change into fine-grained, almost compact rock (eurite), in transverse bands of irregular shape. These bands look as if they were subsequent veins injected into the other granite; but as they are strictly confined to the

[1] "Quart. Journ. Geol. Soc." vol. xii. p. 192-198.

granite veins, and do not penetrate the adjacent slates, it is impossible to attribute such an origin to them. Moreover, in the adjacent granite large irregularly-shaped masses of this compact eurite are to be seen coming in quite suddenly, but with no resemblance to a subsequently intruded mass.

"Other veins, both in the granite and the adjacent slates, are doubtless of subsequent origin; but even in these cases it is probable that they are not of a date long posterior to the intrusion of the main mass of the granite. It is possible that on the first consolidation of the upper

Fig. 140. Elvan traversing Argillaceous Schist, St. Agnes, Cornwall.

portion of the granite, cracks and fissures might take place, into which injections of the yet molten rock below might be forced. The upper consolidated part of the granite, although no longer fluid from heat, might yet retain a very high temperature—might, for instance, be red hot, so that the veins injected into it might be soldered, as it were, firmly to the walls of the fissures."

The veins proceeding from a mass of granite frequently pass into true felsite. The *grey elvans* of Cornwall are broad veins of quartz-felsite or elvanite, differing from granite chiefly in the absence of mica. "Similar 'elvans'

are abundant also near the granite of Leinster, and probably in the neighbourhood of all other granitic masses. They are obviously veins derived from the granite, since that particular variety of rock only occurs in districts where granite also occurs, and they are generally more numerous as we approach the granite. They are often traceable in nearly straight lines for some miles, although only a few feet in width, several of them sometimes running parallel to each other for such a distance, with intervals of several hundred yards between them. They often coincide in strike with the slate or other rocks in which they lie, though they generally cut obliquely across the dip of the beds, and sometimes also across their strike. They often alter the rocks in contact with them; not, however, like the larger granite masses, by converting them into mica-schist, but merely producing a greater induration and a more minute joint fracture, and a brown ferruginous tinge, giving them what might be called a burnt aspect." [1]

The results obtained by Mr. Sorby from a study of the cavities in crystals have already been mentioned (p. 276). The late Mr. Clifton Ward applied Mr. Sorby's method of investigation to the granite of the Lake District, and came to the following conclusions:—

1. That granites and granitoid rocks may sometimes have been the deep-seated foci of volcanic phenomena, and at other times they may have consolidated under a great thickness of rock.

2. That all such deep-seated rocks must have been subject to pressures acting from two directions—a *downward pressure* caused by the weight of the overlying rocks, and a *surplus* or *outward pressure*, acting chiefly from below.

3. That if the depth at which the granite originally consolidated can be approximately determined by geological considerations, we may deduce the relative values of these two pressures, and infer whether the outward pressure was relieved or not by volcanic action. If the depth or downward pressure thus determined tends to coincide with the total pressure indicated by microscopical examination, we may infer that the outward pressure was so relieved; but

[1] Jukes' "Manual of Geology," second edition, p. 316.

if the amount of the downward pressure is greatly exceeded by that of the total calculated pressure, we may infer that the outward pressure was not so relieved.

4. That in the latter case the outward pressure will probably have been spent in the elevation, contortion, and metamorphism of the overlying rocks.

5. That the pressures under which the granites of the Lake District were consolidated, calculated from microscopical examination, ranged from 40,000 to 52,000 feet, the mean value being 47,000, or nearly the same as that for the Cornish granites.

6. That the downward pressure or depth of rock under which they were consolidated was probably in no case more than 30,000 feet; it is therefore unlikely they were connected with volcanic vents, and a large amount of surplus pressure was employed in the work of contortion and metamorphism.

It should be mentioned, however, that the accuracy of these conclusions has not yet been confirmed by any comparison with volcanic granites such as those of Mull and Skye. Moreover, there is much difficulty in drawing any conclusions at all from cavities, as the relative volumes of fluid and vacuity vary much even in the same microscope slide.

CHAPTER XII.

PETROLOGY OF METAMORPHIC ROCKS.

§ 1. *Structure of Metamorphic Rocks.*

METAMORPHISM has already been defined (p. 255), and the various rocks which are included in the Metamorphic series have been enumerated and described so far as concerns their lithological characters and constitution. In the present chapter we have to describe the conditions under which these rocks occur, but before entering upon this subject we must give some account of the structures which specially appertain to metamorphic Derivative rocks, and which often supersede the laminated or bedded structure that they originally possessed. These are the structures known as *Cleavage* and *Foliation*.

Cleavage.—A general definition of cleavage and a description of the lithological characters of slate have already been given (pp. 294 and 296); but there are many other facts connected with cleavage which come more properly within the scope of the present chapter. It has been stated that cleavage is a structure produced by intense compression, and the following statements may be regarded as so many proofs of this assertion.

Arrangement of Particles in Cleaved Rocks.—By microscopical examination Mr. Sorby found that the minute particles of slate lie more flatly in the cleavage planes than in any other direction; whence he inferred that they had been lengthened in the direction of the cleavage planes, or else, if they were originally of unequal dimensions, they have been re-arranged so that the longer axes coincide with the planes of cleavage. In the case of coarse-grained rocks this re-arrangement of the component particles may be easily observed; thus, Sir A. Ramsay describes a con-

glomerate near Llyn Padarn in Caernarvonshire as consisting of slaty pebbles in a slaty matrix, the whole being affected by cleavage remarkable on account of the pebbles being elongated in the direction of the cleavage planes, and obliquely to the bedding.[1]

Mr. Sorby also noticed that the green spots so often visible in slates were always elongated along the cleavage planes, and compressed in a direction at right angles to them, while elsewhere the similar spots were spherical. Since, however, these spots have probably been caused by the decomposition of organic matter, it is very doubtful how far this observation is of value.

The same appearances are exhibited by the fossils which occur in slate rocks; their dimensions are always changed, so that the fossil is distorted, being lengthened in one

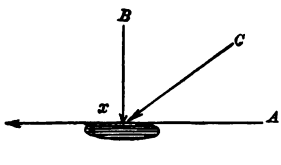

Fig. 141.

direction, and shortened in that at right angles to the cleavage planes. Thin shells such as *Lingulæ* and the tests of *Trilobites* are especially affected, the latter being sometimes minutely wrinkled in lines parallel to the cleavage. If we suppose a force acting from the direction C, upon the body *x*, in fig. 141, this may be resolved into forces acting from A and B, one tending to flatten and broaden it, the other to roll it out; Prof. Haughton has shown that if the fossil originally lay flat in the plane of bedding, the greatest distortion or elongation is in a direction parallel to the intersection of the cleavage and bedding planes.

Mr. Sorby has also shown that when harder beds, such as bands of sandstone or limestone, occur among slates, they are strongly contorted in the manner represented in fig. 142, their dimensions being contracted at the sides,

[1] "Geology of North Wales, Mem. Geol. Survey," p. 145.

and expanded at the tops and bottoms of the curves, while the beds of slate above the sandstone are little, if at all bent. He infers that the particles of the slates must have been compressed at right angles to the cleavage planes, and lengthened along them so as to allow of their being squeezed into the same contracted space as the sandstones, without much bending of the surfaces of the beds. Measurements along some of these contorted bands show that the whole mass has been compressed into one-third of the linear or horizontal space which it originally occupied. Mr. Sorby remarks "that these and numerous other cases in North Devon are analogous to what would occur if a

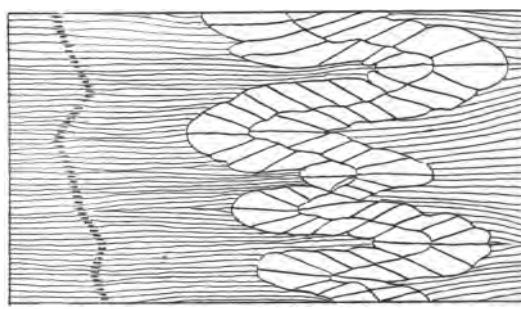

Fig. 142. Contorted Beds in Slate near Ilfracombe (after Sorby).

strip of paper were included in a mass of some soft, plastic material which would readily change its dimensions. If the whole were then compressed in the direction of the length of the strip of paper, it would be bent and puckered up into contortions, while the plastic material would change its dimensions without undergoing such contortions; and the difference in distance of the ends of the paper, as measured in a direct line, or along it, would indicate the change in the plastic material."

Cleavage is always most perfect in the finest grained rocks, splitting them into an indefinite number of thin plates. The coarser the rock, the fainter, the wider apart, and the more rough and irregular do the cleavage planes

become; and in the case of thick-bedded sandstones cleavage generally divides the rock into coarse slabs only, the upper and under surfaces of the beds often breaking into dog-toothed indentations, and thus indicating the compression they have undergone.

Dip and Strike of Cleavage Planes.—The planes of cleavage may be said to have a dip and a strike just in the same way as planes of stratification. Their angle of dip varies from the vertical to as little as 10°, but is more frequently between 50° and 80°. Their strike is generally constant over considerable areas, and parallel to the direction of the axes of the principal flexures. This coincidence between the strike of the cleavage planes, and that of the strata is of itself strong evidence that the cleavage was caused by the same pressure as that which caused the plication of the rocks.

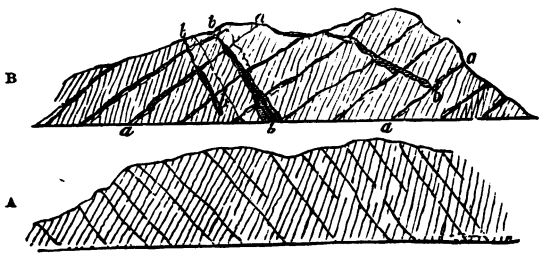

Fig. 143. Relation of Cleavage to Bedding.

Fig. 143 illustrates the varying relations between the inclination of the strata and that of the cleavage planes. A represents a section near Llandovery in Wales, where a series of quartzose grits and sandstones are inclined at an angle of about 40°, and the cleavage planes dip in the same direction, but at a much greater angle. In B the cleavage planes dip in the same direction, while the strata are inclined in the opposite direction. In both cases the strike of the cleavage planes coincides generally with that of the strata.

In some places the cleavage planes coincide in dip and direction with those of the bedding and lamination, as is

the case with the slates and schists at Abereiddy Bay, Pembrokeshire (fig. 144).

One of the best examples of this steady direction in the strike of cleavage planes is the south of Ireland, over the whole of which, from Dublin to Mizen Head, the direction of the cleavage seldom varies much from E.N.E. and W.S.W., whatever rocks it traverses, and however different these rocks may be in lithological character and geological age. The strike of the main axes of flexure is likewise steady in the same direction. The planes of cleavage are inclined at very high angles, which generally approach the perpendicular, but when they have a dip, it is always to the S.S.E., and this southerly dip appears to be connected with the special form of the curves into which the strata have been bent. These are not mere undulations with vertical axes, but are pushed over in a northerly

Fig. 144. Cleavage coinciding with bedding, Abereiddy Bay.

direction, so that their axes are oblique, and the strata are slightly inverted on the northern side, as if the pressure by which they were produced acted most strongly from the south; the dip of the cleavage is therefore roughly parallel to the dip of these oblique axes, both being due doubtless to the same cause.

It may, indeed, be stated as a general rule, that when the axes of the folds and flexures are inclined from the perpendicular, the average dip of the cleavage planes will be in the same direction.

In North Wales the prevailing strike of the cleavage is N.E. and S.W., because this is also the direction of the main lines of flexure; but where the strata are bent round so as to have a different strike, the strike of the cleavage is altered in a similar manner, so as to coincide with that of the beds.

Fig. 145 is a section through the Snowdon chain, from the Menai Straits in a south-easterly direction; the beds, *c c c*, are conglomerates, the other beds being parallel to them, and the fine striæ are cleavage planes striking with the beds to the N.E., but cutting them across in the direction of the dip; for while the beds undulate at various angles, the cleavage dips slightly on either side of the vertical, viz., N.W. at 80° or 85° from A to B; S.E. at 80° to 85° from B to C; and 80° to the N.W. from C to D.

"In the Berwyn chain, where the beds curve regularly round, from a N.E. and S.W. strike along the Bala and Corwen valley, to an E. and W. strike along the vale of Llangollen, the strike of the cleavage follows with equal regularity, the cleavage planes dipping W. 20° N. at 30° in the country between Bala and Llangynnog, curving round as

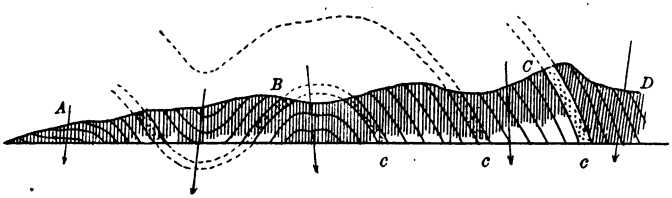

Fig. 145. Cleavage in North Wales (after Jukes).

they approach Corwen, and striking nearly due E. and W. on both sides of the Dee, between Corwen and Llangollen, with a dip almost invariably to the north at a high angle."[1]

Variation in Dip of Cleavage Planes.—As above stated the cleavage generally has a regular dip, and cuts in parallel planes across the strata without paying any regard to their contortions or convolutions, as seen in fig. 145, their direction only varying when that of the beds varies. The inclination of these planes, or the amount of dip, does not usually vary much, but is sometimes curiously affected by differences in the texture of the beds.

Fig. 146 is from a section at Killeen, near Cork, in the Old Red Sandstone. The beds, A A, contain about 80 per cent. of silica, with only small quantities of alumina and iron;

[1] Jukes' "Manual of Geology," 2nd edition, p. 267.

these show no signs of cleavage. The beds, B B, are impure sandstones, containing only 68 per cent. of silica, with 25 per cent. of alumina and iron; these are distinctly cleaved, and split vertically into flags along the cleavage planes. The beds, C C, are intermediate in their characters, containing 76 per cent. of silica, with about 20 per cent. of alumina and iron; and in these the cleavage is not only more imperfect, but has a strong dip to the south.[1] Professors Harkness and Blyth mention other instances in the island of Valentia, where the dip of the planes changes

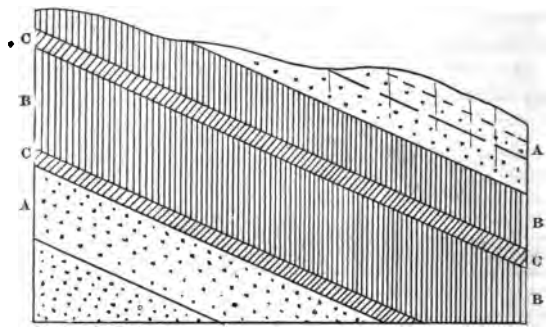

Fig. 146. Variation in Dip of Cleavage.

several times in passing from one bed to another, when these are of different mineral composition.

Cases have also been noticed where the dip of the cleavage appears to have some connection with the dip of the beds. Thus Darwin has described instances in South America where the cleavage planes dip inward on either side of large anticlinal curves, so as to exhibit a fan-like arrangement; but such exceptions to the general rule are probably explicable on the supposition that the dip of the cleavage has been affected by subsequent movements, the cleavage being antecedent in point of time to the production of these particular set of anticlinals. It is quite possible that a district may at one period of time be subjected to very great compression, capable of producing both con-

[1] Harkness and Blyth, "Trans. Edin. Geol. Soc." 1855.

tortion and cleavage; and that after a period of quiescence, during which the beds acquired fixed positions, renewed compression may give rise to another set of curves, or even to a second set of cleavage planes. The range of the Andes is exactly one of the districts where we should expect to find evidences of repeated periods of compression, because there is other evidence that its elevation has been the result of repeated movements (see p. 54).

Cases in which a second set of cleavage planes have been noticed, with a different strike or dip to the first set, are mentioned by Sedgwick, Phillips, and others. Mr. Sharpe describes one in which the beds were traversed by two sets of cleavage planes, one cutting the other at right angles.[1]

Foliation.

The term foliation was originally proposed by Professor Sedgwick, and defined by him "as a separation into layers of different mineral composition," while cleavage means only a "tendency to split" in a mass of the same composition. The foliation of schists appears in some cases to coincide with the planes of cleavage, in other cases with the planes of stratification, and sometimes with those of oblique lamination or ripple drift; but in all cases it is a superinduced structure.

Coincidence of Foliation and Cleavage.—Sedgwick and Darwin were of opinion that foliation was almost always coincident with cleavage, and that it was, in fact, only a further development of the same process. Sedgwick, however, then believed that cleavage itself was produced by the action of crystalline and polar forces, whereas it has since been proved that cleavage is the result of mechanical pressure, and it is difficult to see how there can be any direct connection between cleavage and foliation. A mechanical force may readily communicate a mechanical structure to a mass of rock, but it seems impossible to suppose it capable of producing an alteration in the mineral composition of its particles.

Jukes maintained that the coincidence of foliation with

[1] "Quart. Journ. Geol. Soc." vol. v. p. 3.

cleavage was only an accidental one, and probably it only occurs in cases where a considerable thickness of argillaceous deposits has been converted into a tolerably homogeneous mass of slate before they were subjected to the further metamorphic processes which produced foliation. It is, in fact, only a certain class of rocks, viz., those which contain more or less alumina and magnesia in their composition, which are capable of developing the foliated structure, and the presence of limestones and quartzites in the midst of foliated rocks, where they must have been placed under the same conditions, proves that something in the constitution of these rocks prevented their acceptance of the same structure. The cause is doubtless to be found in the absence of the elements for producing mica and felspar, for unless these elements were supplied from without, the most intense metamorphism, acting on nearly pure quartz or calcite, could not do more than convert them into quartzite and crystalline marble.

Again, it does not seem necessary that the rocks should always have been cleaved before the foliated structure was imparted to them; where, however, a mass of homogeneous rocks already cleaved has been subsequently subjected to metamorphic agencies tending to re-arrange their particles into separate folia, it is quite possible that this re-arrangement might take place along the cleavage planes.

Sedgwick states that sometimes the cleavage laminæ "are coated over with chlorite and semi-crystalline matter, which not merely define the planes in question, but strike in parallel flakes through the whole mass of the rock."

Darwin has also observed the occurrence of epidote in a similar way, viz., in thin layers "parallel to the highly inclined cleavage of the mass."

It must be remembered, however, that since the cleavage planes usually strike with the axes of the principal flexures, and the beds, especially when they approach the vertical position, have necessarily the same general strike, it follows that the cleavage and foliation must necessarily be generally parallel to each other, whether the folia coincide with the cleavage or the stratification. General observations on large groups of rocks may often be deceptive, since concealed curvatures frequently occur in them which

are very difficult to detect when the folds are so sharp that the beds dip in the same direction on either side of the curve; in such cases stratification, cleavage, and foliation may seem to be coincident over large areas.

On the whole, I think it may be said that though in some cases the development of cleavage has preceded the crystallization of the rock, yet it is only in a few instances that the planes of foliation really coincide with those of cleavage, and not with those of stratification.

Coincidence of Foliation with Stratification.—It can be shown, on the other hand, that there are many places where foliation undoubtedly coincides with the planes of bedding. In Leinster, according to Jukes, the folia of the mica-schists are almost always parallel to the interstratified bands of grit, and therefore to the original stratification of the rock, although this was certainly cleaved before the intrusion of the granite which has there caused the metamorphism. In one instance, however, the foliation seemed to run across the bedding, coinciding apparently with the cleavage; but here "the micaceous folia were short and discontinuous, being apparently interrupted by the changes of texture or composition in the original lamination of the rock." It does not seem to have occurred to Mr. Jukes that the folia might in this case have been coincident with oblique lamination. Sir A. Ramsay has described instances in Anglesey[1] where the folia are sometimes parallel with ordinary stratification, sometimes with false bedding or oblique lamination, and sometimes with cleavage, remarking that where they coincide with the false bedding, the foliation appears to cross the planes of stratification, and yet is not coincident with any previous cleavage. Mr. Sorby has also shown that the folia are sometimes arranged obliquely in thin stratulæ, as if they coincided with the laminæ of ripple drift.

In the highlands of Scotland the foliation is usually coincident with the original stratification.[2] This is shown by the intercalation of quartzites and limestones among the schists, the foliation of the latter coinciding with the dip and strike of the former, even throughout the curves of

[1] "Geology of North Wales," Mem. Geol. Survey, Ed. I. p. 177.

[2] Murchison and Geikie, "Quart. Journ. Geol. Soc." vol. xvii.

small contortions, and exhibiting, therefore, a strong contrast to the behaviour of cleavage planes.

Mr. Sorby's recently published researches[1] clearly prove that foliation is essentially different from either cleavage or stratification, and that "it is the result of the varying segregation of different minerals controlled by various previously-existing structures." Microscopical examination demonstrates that in schists where the foliation coincides with stratification, "the flat crystals of mica lie in the plane of the beds of different mineral composition;" while in other cases he finds "a foliation due to large plates of mica lying in a plane corresponding to true slaty cleavage, inclined at a high angle to the stratification, and parallel to the axis planes of the larger contortions." Frequently, also, there is an intermediate kind of structure, in which the stratification-foliation has been bent and crumpled, and a little mica has crystallized along the cleavage planes. Mr. Sorby concludes that "these differences in the character of the foliation appear to have depended on whether or not the rock became completely solid and crystalline before it was compressed, or was compressed before it became solid and crystalline. The intermediate varieties were probably formed when there was a partial metamorphism before compression, and further crystallization afterwards."

The folia of schists are frequently wrinkled and corrugated in a remarkable manner, giving the rock a peculiar crumpled and gnarled appearance. Sir A. Ramsay has suggested that these very lines are those of a previously induced cleavage which was only partially obliterated by the foliation, the planes of cleavage being bent and crumpled by farther pressure when the mass was in a plastic condition. This explanation assumes the existence of a previous cleavage, and it is possible that the corrugation is simply due to subsequent compression acting on the folia of a schist, and that it is therefore analogous to the crumpling of the original laminæ of a slate. It may be the effect of pressure acting on the mass after the process of crystallization had been completed, and when the rock-particles having been already fixed in one direction, the pressure could only crumple the layers or folia thus formed.

[1] "Address to Geol. Soc. 1880," p. 81 *et seq.*

§ 2. *Areas of Metamorphism.*

Having described the structures of cleavage and foliation which are the invariable accompaniments of metamorphism, we proceed to consider the petrological relations of metamorphic rocks, and shall conclude by indicating the causes or agencies which have been concerned in producing them. It is clear that before we can arrive at any complete theory of metamorphism, so as to realize the conditions under which stratified rocks have been converted into slates, schists, and crystalline gneissic rocks, we must study the facts in the field, and the best way of placing them before the reader will be to describe some of the localities and areas where metamorphic rocks are found.

There are districts where metamorphic action has been very intense and very extensive, such as the Scottish Highlands, Scandinavia, and the central Alps, where all the rocks over wide areas have been more or less metamorphosed; but these cases are less instructive in some respects than others where the alteration has taken place on a smaller scale and to a less extent, and where the nature of the results can be more readily grasped. It will be convenient, therefore, to approach the subject by first examining cases of partial and local metamorphism, where the relations of altered and unaltered rocks are clearly visible, before proceeding to the consideration of large areas of metamorphic rocks, where the phenomena are necessarily much more complicated.

Local or Contact Metamorphism.—Some of the metamorphic effects produced by the intrusion of igneous rocks have already been mentioned. The mutual alteration occasioned by the contact of dolerite and coal was described at p. 411, and the similar effects resulting from the contact of granite veins with limestone on p. 425; again, the manner in which a mass of slate may be altered into mica-schist by the intrusion of granite bosses was illustrated in fig. 137. But in order to understand the nature of the process by which such effects are produced, it is requisite that these and other similar instances should be more closely and minutely examined.

Alteration by Dykes.—1. A simple instance of local meta-

morphism is presented by the chalk in contact with the basaltic dykes of Antrim. By the intrusion of these dykes the chalk has been converted into a crystalline stone; the amount of alteration being greatest near the basalt, and gradually decreasing outwards, but sometimes extending to a distance of 8 or 10 feet from the wall of the dyke. "The extreme effect," says Dr. Berger, "presents a dark brown crystalline limestone, the crystals running in flakes as large as coarse primitive (*i.e.* metamorphic) limestone; the next state is saccharine, (gradually becoming) fine-grained; a compact variety having a porcellanous aspect, and a bluish grey colour succeeds; this towards the outer edge becomes yellowish white, and insensibly graduates into the unaltered chalk."

The annexed sketch, fig. 147, represents the plan of three

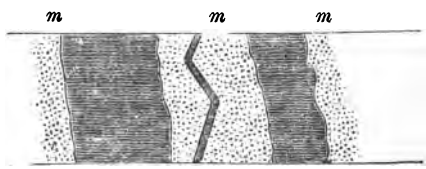

Fig. 147. Alteration of Chalk by Basalt Dykes, Antrim.

dykes as seen on the beach of Rathlin Island, Antrim, which have altered the contiguous portions of the chalk, *m m*, into the granular marbles above described.

2. Another instance of the powerful effect of a dyke has been described by Prof. Henslow as observed near Plas-Newydd in Anglesea. In this case a broad dyke of dolerite traverses strata of shale and argillaceous limestone; the metamorphic effect begins to be perceptible at a distance of about 30 feet, the shale becoming compact and indurated, and losing its fissile character, though the lines of lamination are still visible; near the dolerite it is converted into a hard jaspery porcellanite, while crystals of garnet and analcime are developed more or less throughout the altered portion of the shale. The limestone undergoes similar alteration, becoming gradually compact and crystalline in approaching the trap.

Alteration by Granitic Masses.—1. As an instance where

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the effects of intrusive bosses of igneous rock can be easily examined we may take those of Cornwall. In this county four bosses of granite, which are probably parts of one continuous underlying mass, are intruded into the clay slates which are locally termed *killas*. The metamorphic zone surrounding any of these bosses varies from a quarter to half a mile in width; within these limits the killas is converted into micaceous schist, and in the immediate neighbourhood of the granite the rock has been re-crystallized into felspar and hornblende, so as to become a regular hornblende schist. Where the killas contains interbedded layers of argillaceous grit, these have been converted into a kind of felspathic quartzite or granulite, which bears so much resemblance to granite that, at first sight, some of them might be taken for intruded tongues of that rock, though a careful examination shows that the crystals of quartz and felspar have a hazy and indistinct outline. See also description of Dartmoor granite, p. 421.

2. The metamorphism of the Silurian slates by the granite of Leinster, already described (pp. 382 and 419), supplies an instance in which a still wider zone of rock has been altered in a similar way. Mr. Jukes has given the following description of this district:[1]—"The great mass of granite which has been intruded into the clay slates of Leinster forms a continuous range of granite hills from Dublin Bay to the neighbourhood of New Ross, a distance of 70 miles. Between this range and the coast other smaller intrusive bosses make their appearance at the surface. The unaltered clay slates exhibit various tints of dull grey, green, blue, purple, and black; they are always without lustre, and generally of a dull earthy texture. Small bands of grey siliceous grit often occur in them.

"Wherever the granite comes to the surface a belt of slates surrounding it is converted into mica-schist, with, in some few places, beds that might be called gneiss. Crystals of garnet, schorl, andalusite, staurolite, &c., make their appearance in these altered slates in greater and greater abundance as they approach the granite. The width of the metamorphosed belt is generally proportioned to the

[1] "Students' Manual of Geology," second edition, p. 275.

size of the granite mass which it surrounds. Round the smaller granite bosses it is sometimes not more than 50 yards wide; round the main granite mass it sometimes reaches to two miles. It matters not through what part of the slate rocks the granite rises, or which beds strike towards the granite,—they are all found to be affected in the same way as they approach it.

"In going towards the main granite ridge it is found sometimes at a distance of two miles from the outcrop of the granite (which is, however, much nearer probably in a vertical direction), that the slates have acquired a 'glaze,' as it were, or micaceous lustre, with a soapy feel. This lustre is apparent throughout the mass when the slates are broken, and even when they are ground down into sand or powder. This micaceous appearance increases as we approach the granite, till at last distinct plates and folia of mica are to be seen, and the whole assumes the ordinary character of mica-schist, occasionally passing into a kind of gneiss.

"Some of these gneissic layers are obviously beds of sandstone originally interstratified with the shales, the rocks having all the appearance of interstratified shale and sandstone at a distance, and until they are broken open, and are found to have the aspect of mica-schist and gneiss."

By French writers the term *aureole* has been introduced to designate the concentric zone of metamorphosed rocks which surrounds an intrusive mass of igneous rock. Thus, in describing the phenomena of contact metamorphism round the granitic bosses of Asturia in Spain, M. Barrois says: "The first metamorphic effect is simply a change of structure, consisting of the development of a crumpled or goffered structure, without any new combinations being formed among the elements of the rock. Nearer the granite the metamorphic effect is different and more intense; the minerals whose substance is disseminated in a pulverized state within the rock have crystallized in consequence of molecular changes, the particles of a similar nature being attracted to one another," and forming crystals of mica, chiastolite, &c.[1] Such rocks are elsewhere

[1] "Recherches sur les terrains anciens des Asturies et de la Galicie, Mem. Soc. Geol. du Nord," tome ii. 1882, p. 92.

known as *spotted schists*, *schistes maclifères*, and *knoten-schiefer*. These chiastolite schists become more and more micaceous as one approaches the granite, until they become typical mica-schist. Three distinct concentric *aureoles* can, therefore, be recognized round the crystalline masses of Asturia, and may be distinguished as follows, commencing with the outermost:—

1. Aureole des schistes gaufrés (wavy schists).
2. Aureole des schistes maclifères (spotted schists).
3. Aureole des Leptynolithes (mica-schists).

M. Barrois is careful, however, to point out that this succession of aureoles is only true in a general sense, and that layers of micaceous schist with crystals of chiastolite are often intercalated among the less highly metamorphosed schists. Such intercalations are doubtless dependent upon differences in original mineral composition, the crystals being more easily developed in some beds than in others.

Chemists have demonstrated that the ultimate composition of slates or schists is that of a mixture of quartz and mica. "Now we see in the passage from argillaceous schist into andalusite schist and quartzose mica-schist, the quartz and the mica becoming more and more individualized, while the excess of alumina is concentrated into distinct crystals of certain silicates of alumina (andalusite, chiastolite, &c.)." [1]

Regional Metamorphism.—The cases of alteration above described demonstrate that the intrusion of igneous rock into stratified rock is sufficient to convert the latter into substances which are mineralogically identical with some of those which are known as metamorphic rocks. Moreover, since the extent of this metamorphism appears to be roughly proportionate to the mass of the intrusive rock, it might be supposed that the cases of metamorphism on a larger scale were principally due to the proximity of still larger masses of intrusive igneous rocks. This, however, would be a false inference, for we could not examine many metamorphic districts without finding that the extent of metamorphism was out of all proportion to the mass of purely intrusive rock in the same area. The Scottish Highlands, for instance, are one vast mass of metamorphic

[1] Barrois, op. cit. p. 104.

rock, yet they do not exhibit any mass of intrusive granite so large as that of Leinster, the alterative effect of which only extends to a maximum distance of two miles. Again, in the Swiss Alps, where whole mountain masses consist of highly metamorphosed strata, intrusions of granite or other plutonic rock are of rare occurrence, and where they do exist are on a comparatively small scale.

It is clear, therefore, that the mere contact with deep-seated igneous rock is not sufficient to produce wide areas of metamorphism; but the same study of metamorphic districts which would lead us to discard this hypothesis would elicit the fact that metamorphic action has always been accompanied by great contortion and plication of the strata, and that the amount of this plication does appear to have a direct relation with the intensity of the metamorphism.

We have already seen that folding and contortion may reasonably be attributed to forces producing lateral compression. It is also a matter of observed fact that most of the great mountain chains of the world consist mainly of contorted, cleaved, and metamorphic rocks (see Part III., p. 458); in such regions everything points to the combined influence of pressure and heat, with a resulting movement of elevation. Mr. Mallet has also suggested that the energy of the force employed in crushing and contorting the rocks may be transformed into heat, and that the amount of heat evolved during this process might sometimes be sufficient to soften and partially fuse the rocks which are thus affected.

Since, therefore, the temperature will be highest where the compression is greatest, it is only natural that we should always find metamorphism to be accompanied by evidences of intense compression. There is indeed some more direct evidence that the rocks of highly metamorphic districts have been consolidated under greater pressure than in the cases of contact metamorphism already mentioned. Thus Mr. Sorby found, by means of the method already explained on p. 276, that the granites of the Highlands indicate a pressure of 26,000 feet more than those of Cornwall, and that the metamorphic rocks of the Highlands indicate one of 23,700 feet more than those of Cornwall.

It is, therefore, a wide-spread belief that such tracts as the Scottish Highlands and the Swiss Alps are areas of regional metamorphism, that is to say, are areas consisting entirely of rocks which have been more or less metamorphosed by the combined effect of great vertical and lateral pressure acting under a high temperature, and in the presence of water or water-vapour: such rocks being now exposed at the surface in consequence of the removal of the material which once overlay them.

But although there is no *à priori* reason why these views of regional metamorphism should not be correct, especially in the case of districts composed of the older rocks, yet it is certain that for many of the instances which have been brought forward the evidence is inconclusive, and that most of the metamorphic regions which have been recently and thoroughly examined prove to be composed of the most ancient (Archæan) rocks, which are invariably metamorphic wherever they occur.

The Ardennes, comprising the mountainous region which runs through the north of France and south of Belgium eastward into the basin of the Rhine, has been considered a good example of regional metamorphism. The district has been recently studied by M. Renard,[1] who points out that this metamorphic band occurs along a line of plication running in a general E.N.E. and W.S.W. direction, and that it is not associated with any visible eruptive rocks; that the metamorphic rocks die away into ordinary unaltered greywacke and shale on the outside, and become more and more crystalline towards the axis, until they present an example of the most intense metamorphism.

He insists that the microscopical study of the rocks entirely confirms Dumont's view that their present condition is the result of metamorphic action; and he connects this metamorphism with the proofs of great plication and contortion which are observable through the whole district. "The mechanical action involved in the process of compression, would, he believes, predispose the sedimentary materials to a more or less complete re-crystallization. As it crushed them under the enormous pressure, and

[1] "Bull. du Mus. Roy. Hist. Nat. de Belgique," tome i. 1882.

partly was itself transformed into heat, it would set into active motion the chemical affinities of the various mineral substances. In this way sand might finally pass into quartzite, argillaceous mud into phyllade or phyllite schist, sandy clay into more or less schistose micaceous quartzites; the calcareous matter would enter into combination to form the various lime silicates so characteristic of these garnetiferous and hornblendic rocks; while the carbonaceous ingredient, losing some of its constituent elements, would separate out as graphite."[1]

The Ardennes may, indeed, be a region where a small amount of metamorphism has been developed by pressure; but there are no true crystalline mica-schists or gneisses to be found among the Devonian rocks of the district; and if such crystalline rocks do occur it is among the older rocks which are now known to exist in the central parts of the Ardennes.

Metamorphic Granite.—It was mentioned at p. 297, that in some localities a complete passage can be traced from an ordinary gneiss into an evenly crystalline compound of quartz, felspar, and mica, which appears to be a genuine granite; in other words, that large masses of rock, which are lithologically granite, are geographically nothing but gneiss.

It is quite possible that at great depths extreme metamorphism may take place, resulting in the complete fusion of certain rocks containing the elements of granite, and portions of this material might become so plastic or fluid as eventually to be injected into the cracks of the overlying rocks, and thus become a true intrusive granite. Some geologists, indeed, believe this to have been the origin of all granitic and syenitic rocks.

In some instances it certainly seems as if such a melting down of stratified rocks had taken place, the gradation from the unaltered rocks into granite being so gradual that we can hardly escape the conviction that some of the granite really represents a mass of strata in a state of complete metamorphism. One instance will suffice.

The mapping of county Galway by Mr. G. H. Kinahan,

[1] Dr. A. Geikie in "Nature," vol. xxvii. p. 121 (1882).

and other members of the Geological Survey of Ireland, disclosed the existence of two kinds of granite in that region. "Of these, one is of intrusive character, sending veins into the adjacent rocks, and containing one kind of felspar only (viz., orthoclase), while the other contains two felspars (oligoclase as well as orthoclase), the orthoclase often occurring in large pink crystals, giving a porphyritic character to the rock. Where the junction of this porphyritic granite with the metamorphic rocks can be clearly seen, it is often to be observed that the granite passes insensibly into the surrounding gneiss. This is caused by the flakes of mica assuming gradually a parallelism in the rock, giving it more and more a foliated character, till it is difficult to say where it passes from granite to gneiss. With true intrusive granite, there is never any such difficulty."[1]

It is possible, however, that future microscopic examination may show that this peculiar granite is only porphyritic gneiss, and it must be admitted that many of the instances which have been put forward as demonstrating the passage of metamorphic rocks into granite, are capable of a very different explanation (see p. 258), and may only be cases of metamorphism by contact with intrusive granite. The descriptions given of the granites of the Pyrenees, and of Priestlaw, in Berwickshire, cannot be considered as proving the metamorphic origin of granite. Still less satisfactory is the so-called metamorphic granite of Ayrshire; the very facts described by Dr. J. Geikie[2] being sufficient to demonstrate its intrusive nature. The rocks of the country are felspathic sandstones with shales and mud-stones interstratified occasionally; amongst these are tracts and patches of typical granite. Dr. J. Geikie observes that the dip and strike of the stratified rocks continue unchanged till they begin to assume a baked aspect and semi-crystalline texture, and that on the other side of the granitic and metamorphic area they again appear, with exactly the same dip and strike. He further shows that it is only where the sandstones come into contact with the

[1] Jukes' "Manual of Geology," third edition, p. 247.

[2] "Geol. Mag." iii. p. 529, and "Mem. Geol. Survey of Scotland," expl. of sheet 22.

granite that there is a passage between the two kinds of rocks; and that where the slaty shales impinge upon the granite, the line of junction is easily distinguishable. They are, in fact, cases of truly intrusive granite surrounded by *aureoles* of metamorphic rocks like those already described; the felspathic sandstones being more susceptible of metamorphism than the shales, and containing moreover the precise ingredients for transformation into a granitoid rock.

The cases in which layers of granite or granitoid rock are distinctly interbedded with thick beds of mica-schist and gneiss are at first sight more convincing, because when traced in one direction the beds of granite and gneiss become thicker, and the intervening bands of mica-schist are thinner and fewer, till at last the ground is wholly occupied by granite. Such a case is to be found in the district of Errigal, county Donegal, Ireland; but this may, perhaps, be explained by supposing the whole metamorphic area to be underlain by a mass of granite comparable to that of Leinster. The diverse strata dipping down on to this granite have been more or less metamorphosed according to their mineralogical composition,—pure sandstone into quartzite, limestone into marble, shales into mica-schist, and certain bands of mud-stones or felspathic sandstones into gneiss and granitoid rock.[1]

Notwithstanding the doubt that hangs over the metamorphic origin of certain granite, the possibility has been very generally accepted; and just as a connection has been traced between some granites and certain volcanic rocks, so it has been thought that other granites may result from the extreme stage of metamorphism, and that the process which can produce gneiss only requires to be carried a stage further for the production of granite.

On this subject Dr. A. Geikie thus expresses himself:[2] "It seems to me not only conceivable, but probable, that, whether melted by depression into the heated interior of the earth, or by the high temperature produced during

[1] Originally described by R. H. Scott, "Journ. Roy. Geol. Soc. of Ireland," vol. i. p. 144; vide account in Green's "Physical Geology," second edition, p. 265.

[2] In "Trans. Edin. Geol. Soc." vol. ii. pt. iii.

compression and contortion, granite may sometimes have been formed in the midst of crumpled and metamorphosed rocks, and intruded into them in bosses and veins; while, at other times and places, coming in contact with the aqueous circulation in the upper part of the crust, it gave rise to the ordinary phenomena of volcanoes. Hence I can believe that, even in the same mountain range, one mass of granite may be simply the extreme form of the metamorphism of rocks, *in situ*, under which it remained always deeply buried until exposed by denudation, while another mass, originally formed in exactly the same way, may be the lower end of a column of melted material of which the upper portion reached the surface of the earth, producing there streams of lava and showers of ashes."

We may, therefore, with Sir Charles Lyell, regard the whole crust of our globe as consisting of materials passing through an endless cycle of mutations, existing at one time as igneous rocks, then gradually decomposed, broken up, sorted and deposited as aqueous rocks, buried under fresh accumulations, metamorphosed and ultimately re-absorbed into the igneous rocks. In this view the most highly metamorphosed rocks would be those hovering upon the brink of re-absorption, and gneiss accordingly on the brink of passing into granite, and often almost undistinguishable from it.

PART III.

PHYSIOGRAPHICAL GEOLOGY.

THE first chapter of this book treated of the earth as a whole, and the opinions entertained with regard to the general structure of its mass and the condition of its interior were there given. In the chapters of Part II. the structure and arrangement of the rock-masses which compose the superficial portion of the earth's crust were described. We are now in a position to deal with the problems of Physiographical Geology, or that branch of the science which seeks to account for the existence of the varied physical features of the earth's surface, and explains the manner in which oceans and continents, mountains and plains, hills and valleys, have been gradually developed out of the rock-masses by the machinery of the physical agencies described in Part I.

CHAPTER I.

THE ORIGIN OF CONTINENTS AND MOUNTAIN CHAINS.

IT is well known that nearly three-fourths of the earth's surface are depressed below the rest, and are covered by salt water. These depressions are called *Oceanic basins*, and the intervening areas of dry land are termed *Continents* or *Continental plateaux*. Certain portions of the continents rise to a still greater elevation, and form long ridges or *mountain chains*. It is the origin of these larger features of the earth's surface that will be discussed in the present chapter, leaving the minor features which diversify the surface of the continents to be considered in the next.

It has been pointed out by Professor Dana and others that the arrangement and relative position of oceans, continents, and mountain chains is peculiar and significant. The facts may be stated as follows, and may guide us in considering the probable origin of these great features.

1. Mountain ranges are chiefly developed along the borders of continents, and enclose basin or trough-shaped areas.

2. The highest mountain ranges face the largest and deepest oceans.

3. All mountain ranges are formed of rocks which have been subjected to enormous lateral compression.

4. Mountain ranges have been produced by several successive uplifts and are of different ages.

General Form of Continents.—In support of the first proposition we may take a brief glance at the larger surface-features of the great continents.

North America has the ranges of the Rocky Mountains and Sierra Nevada on the west; the Alleghany range on

the east; with the great plains of the Mississippi basin between them.

South America has the great chain of the Andes all along its western border, the Brazilian ranges on the east, and other mountains along the northern border, while the central portion consists of low plains traversed by great rivers. A transverse section across the centre of this continent would appear as in fig. 148.

Africa has ranges of mountains parallel to all its coasts. The interior of the southern half of the continent consists of vast plains, with an elevation of from 1,500 to 2,000 feet above the sea, and bounded on all sides by mountain chains. The northern half is of similar construction, but the average level of the Sahara desert is much less, and descends in some parts below the sea-line.

Fig. 148. Section through South America.
a = Andes. *b* = Brazilian highlands.

The Europasian continent does not present such regularly disposed ranges of mountains. Nevertheless we find the Scandinavian chain on the north-western border, and a succession of lofty ranges traversing its southern regions—viz., the Pyrenees, Alps, Balkans, Caucasus, Hindoo-Koosh, and Himalayas,—while the Yunling, Khingan, and Stanovoi mountains are parallel to its south-eastern border. The interior may be said to consist of three great areas of comparatively level land, separated by mountain ridges—viz., the Urals between Russia and Siberia, the Thian Shan and Altai ranges between Russian and Chinese Asia.

Australia is eminently basin-shaped, having ranges of hills and mountains parallel to most parts of the coast, while the interior is an arid plain, most of which is but little above the sea-level.

Depth of Oceans compared with the height of Mountains.—To prove the truth of the second statement—that the height of the mountains bordering a continent is generally proportional to the depth and extent

of the neighbouring oceans—it is evident that we must know the relative depth of the great oceans of the world. It seems tolerably certain that the Pacific is at once the largest and deepest ocean; soundings have been taken across it in many directions, and from these the following results have been calculated. The northern part of the Pacific Ocean appears to have a mean depth of 16,000 feet, and the southern part of the same, one of about 13,000 feet, the mean depth of the whole ocean being about 14,500 feet, and the maximum depth yet discovered being nearly 28,000 feet.

The Atlantic Ocean must be divided into three sections, the extreme northern parts between Ireland and Nova Scotia being much shallower than the rest, and having a mean depth of only 8,800 feet. The mean depth of the equatorial parts of the Atlantic appears to be about 13,500 feet, and that of the South Atlantic about 13,000 feet. The mean depth of the whole is by the same calculation 12,600 feet, and the deepest sounding is 23,250 feet near Bermuda.

The depths of the Indian Ocean have not been so fully explored, but the average soundings appear to be about 2,200 fathoms, or 13,200 feet. Its mean depth, therefore, appears to be intermediate between that of the Pacific and Atlantic, but not much greater than the latter.

The Arctic Ocean is a very shallow one; and that part of it which lies to the north of Europe and Asia does not often exceed a depth of 1,500 feet.

The Mediterranean Sea, on the other hand, though its surface area does not entitle it to be called an ocean, has an average depth nearly equalling that of the North Atlantic. A submarine ridge, extending between Sicily and Africa, divides it into two basins, the western of which has a central depth of more than 9,000 feet, and the eastern basin descends to one of 13,800 feet.

Let us now examine the relative heights of the mountain ranges we have mentioned. Taking North and South America together, we find that the highest ranges—those of the Rocky Mountains and the Andes—face the Pacific Ocean. In Africa the average height of the three chief ranges is nearly the same, the Atlas attaining a height of

11,400 feet, the Drakensberg, in Natal, 10,300 feet, and the western hills (Benguela) 10,000 to 13,000 feet. The greatest heights occur, however, on the eastern side of the continent; Kilimanjaro, near Victoria Nyanza, being about 20,000 feet high, and the Abyssinian heights reaching to nearly 16,000 feet.

In Europe we have the lowlands of Lapland and Russia facing the shallow Arctic Sea, while the lofty ranges in the south (Pyrenees, Alps and Caucasus) are nearly equalled by the depths of the Mediterranean. Asia presents exactly the same phenomena, the plains of Siberia facing the Arctic ocean, while lofty ranges of mountains face the depths of the Indian and North Pacific Oceans.

In Australia we have the counterpart of America; the mountains along its eastern border, facing the Pacific, being far higher than any of the others. Mount Lindsay is 5,700 feet, and Mount Koskiusko 7,300 feet high.

Evidences of Compression.—The proofs of the third statement made on p. 455—namely, that the rocks composing mountain ranges give evidence of having been subjected to great lateral pressure—are to be found in the following facts:—

1. These strata are always greatly folded and crumpled, the contortion increasing toward the central axis of the chain (see p. 346).

2. The whole mass is generally bent upwards into a series of long folds, the axes of which are parallel to the length of the chain.

3. The rocks exposed in the central parts of the chain are generally such as have been metamorphosed by the combined influence of pressure and heat.

4. Mountain chains appear to have roots—that is, the crust appears to be thicker beneath them than it is elsewhere. There are two considerations which lead to this conclusion: A. The fact that mountain chains attract the plumb-line, but in a degree less than is proportionate to their visible mass. It has been calculated how much attraction ought to be attributed to the mass of the Himalayas, and it was found that they ought to have attracted the plumb-line more than they actually did. Sir G. B. Airy has explained this anomaly by the supposition that

there is a still greater protuberance of rock downwards into a denser yielding substratum than there is upward into the air. B. That pointed out by Mr. O. Fisher, that the downward increment of temperature is less beneath mountains than beneath plains, as it should be if there were a greater thickness of rock beneath the former.[1]

Age of Mountain Chains.—The fourth statement, on p. 455, was to the effect that mountains have not been formed by one single uplift, but by successive uplifts, with perhaps long intervals between the movements. This is

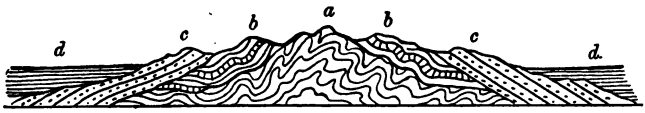


Fig. 149. Diagram showing three Periods of Upheaval.

easily proved by the relative position of the strata on the flanks of a mountain range.

Thus, in fig. 149, if the group marked *a* are crumpled and metamorphosed rocks forming the axis of the chain, and are overlaid unconformably by the group *b*, it is clear that the former group must have been disturbed and elevated before the deposition of the latter (see Part II. Chapter IX.); again, there must have been an uplift between the deposition of *b* and *c*; and, lastly, the group, *c*, was tilted and eroded before the deposition of the beds, *d*, which are undisturbed.

Here, therefore, there is evidence of three successive uplifts; but as the movements ceased before the deposition of the beds, *d*, the chain is said to date from the last period of elevation—viz., that between the epochs of *c* and *d*.

But we might find another mountain chain where only the rocks older than *c* were contorted and tilted, the strata of *c* itself being horizontal and undisturbed. In this case the elevation of the chain was completed between the epochs of *b* and *c*, and is therefore of older date than the first case.

[1] "Physics of the Earth's Crust," pp. 152, 281.

To a certain extent the height of mountain ranges seems to be proportional to the recency of their latest uplifts. The last uplifts of the Himalayas, the Pyrenees, the Alps, the Andes, and the Rocky Mountains have all taken place in late geological times; while the Highlands of Scotland and Scandinavia, the Ourals, Carpathians, and other less important chains, are the worn-down stumps of much more ancient ranges of mountains. It may also be observed that in the case of several parallel chains, the newer are generally on the seaward side of the older ranges.

The Hypothesis of Secular Contraction.—From the preceding facts and statements it would appear that the continents are great masses of land which rise out of the ocean depths, and that their borders are corrugated and ridged into long mountain chains, which give evidence of having been produced at various times by means of great lateral compression. Let us see, therefore, whether the theory that the earth is a cooling globe will furnish us with any probable explanation of these phenomena.

We saw, in Chapter I., that there was good reason for believing that the earth has always been losing heat by dissipation into space, and that it at one time contained much more heat than it does at present. Now it has been ascertained by experiment that all rocks expand when heated, and contract when cooled; and it has been assumed that when they pass from a fluid or pasty condition into a solid crystalline state, the contraction they undergo produces a considerable diminution of their volume.[1] Hence, it is said, that if the earth is a cooling globe, it is also a contracting globe, and that its mass has been continually shrinking in volume, so that every portion of it has been compelled to occupy less and less space.

Experiments have been made on various rocks to ascertain the actual amount of contraction they undergo in passing from a fluid to a solid state. Bischof experimented upon granite, trachyte, and basalt, and according to his results it appeared that granite contracts 25 per cent., trachyte 18 per cent., and basalt 10 per cent. Subsequent

[1] It is not certain, however, that liquid lava or gramite is less dense than when in a solid form, see "Physics of Earth's Crust," p. 23.

investigations, however, have thrown some doubt upon these results, and those arrived at by M. Delesse are probably nearer the mark. His experiments showed that the more acid rocks (granite, felsite, &c.) contracted more than the basic rocks (basalt, &c.), but that the amount of contraction never exceeded 10 per cent., and was more often between 3 and 7 per cent. Mr. Mallet's experiments indicate a still less amount of contraction in the case of ordinary slag. M. D'Archiac remarks that if we assume granite to contract as much as 10 per cent. on cooling, and if there be a thickness of 40,000 metres (51,000 yards) of granite in the crust of the globe, crystallization alone would diminish the terrestrial radius at least 1,430 metres (1,830 yards), and consequently would alter the form and the rapidity of rotation of the earth. It is not likely that such a mass of granite ever consolidated at one time; still it is clear that the heating necessary for the conversion of any mass of rock into granite beneath any portion of the earth's surface would be accompanied by a great expansion, and an uplifting of the rocks above it. Similarly, the cooling of any mass of granite must be accompanied by a corresponding amount of contraction, and a consequent subsidence of the overlying rocks. Such expansion and contraction would therefore produce movements of elevation and subsidence.

At present, however, let us only consider the gradual contraction of the earth's mass caused by the continual dissipation of heat. The materials of the earth conduct heat very badly. Consequently the surface, being exposed to the sky, would become covered with a cooled crust, while at a very moderate depth the temperature was still enormously high; just as a lava stream can be walked over while it is still molten inside. The circumference of the crust so formed would be that of the very hot globe. As time went on, the heat from within would pass out through the cooled crust, and this would be accompanied by a shrinking of the interior. But the outside of the crust was cooled while the globe was larger, and although it will have grown thicker, still it will remain too large for the shrunken interior, upon which, therefore, it will settle down by its own weight.

It is impossible, however, that there could be any disseverance or break of continuity between the outer and inner portions of the contracting globe, for no part of the earth's crust could stand without support from below: the power of gravitation (or the weight of its own mass) must crush in this outer crust and force it to accommodate itself to the diminishing circumference of the contracting interior.

It requires only an elementary knowledge of mechanical principles to perceive that the inward pressure of a rigid arched envelope or crust must necessarily be converted into enormous lateral pressure. If the interior of the globe is drawing away from the outer crust, we may look upon the crust as subjected to vertical forces acting equally from every direction, and it is clear that these forces will be resolved into tangential forces causing lateral pressure in every portion of the earth's crust.

This lateral pressure would produce very powerful compression and crumpling of the rocks composing that crust, resulting eventually in their bending, breaking, and ridging up along certain lines. In other words, the crust could only continue to embrace the nucleus by a process of crushing and crumpling, and this process would continue whether the interior were solid or liquid.

If, therefore, this conception of the mode in which compression of the crust has proceeded is correct, if the crust has become wrinkled and contorted in consequence of its closing in upon the shrinking interior mass of the globe, then there is no doubt that the pressure thus generated would be amply sufficient to cause elevations and depressions of the surface, and might by its repeated action develop such features as oceans, continents, and mountain chains, if the globe contracted enough.

It must be remembered, however, that though the amount of pressure produced by such contraction would be capable of performing the work required, yet it by no means follows that the work was actually accomplished in that way. Compression would doubtless be the result of such contraction, but it can also be produced by expansion of the crust.

Objections to the Theory of Contraction.—Until quite recently there was a strong disposition among geologists to accept the hypothesis of contraction as sufficient in itself to

account for the existence of continents and mountain chains. Mr. O. Fisher, however, has put the hypothesis to the proof, and comes to the conclusion that it is inadequate to account for the production of these features.[1] He admits that the great inequalities of the continental surfaces have been caused by lateral compression, but does not believe that this has arisen from the secular cooling of the earth's mass.

Mr. Fisher considers the hypothesis on two separate assumptions: first, that the earth is solid, and has cooled as a solid; second, that there is a liquid substratum between the solid crust and the solid nucleus.

1. On the first assumption all the inequalities produced by compression arising from contraction would be of the nature of elevations above a certain datum level. There could be no actual, but only relative, depressions, and the bottom of the ocean-basins would either coincide with this datum level or would be the parts that were least raised above it. Proceeding on this assumption, he calculates that the whole of the existing inequalities of the earth's surface (above the said datum level), including the ocean basins, if levelled down and spread out, would form a uniform layer of about 10,000 feet in thickness.

He then shows that it is possible to estimate the amount or volume of the inequalities which would be produced by the contraction of a cooling solid globe; and that even on the most extravagant suppositions the layer formed by the inequalities so produced would not exceed 900 feet in thickness, and would probably be not more than 200 feet. The large discrepancy between these numbers (10,000 and 200 or even 900) shows that this assumption is untenable.

2. On the second, and on geological grounds, more probable assumption, that there is a yielding substratum between the crust and the solid interior, the amount of contraction necessary to produce the existing inequalities must be estimated in a different way.

Proceeding on the most probable suppositions, that the oceans lie in veritable depressions of a denser crust, and that compression is confined to the continental areas, he

[1] "Physics of the Earth's Crust," p. 73.

shows that the total amount of requisite radial contraction, *i.e.*, the contraction measured along a radius from the earth's centre, would be about 42 miles; whereas from physical considerations he places the extreme amount of radial contraction which has actually taken place at only 1·9 miles. This latter calculation is indeed made on the assumption that the earth is solid throughout, but he says, "if we regard the crust as resting on a liquid substratum, it does not appear how its contraction through mere cooling can have been so much greater than in the case of a solid globe as to account for what the latter will not explain."[1] Consequently, Mr. Fisher comes to the conclusion that the hypothesis of contraction by cooling is not adequate to account for the observed phenomena. With regard to this estimate as to the requisite amount of radial contraction, Mr. Fisher has kindly informed me that with a proper and complete interpretation of the symbols used in his calculation, the conclusion may be stated as follows:—"Suppose the mountains and their roots to be pared off and put aside as fast as they were formed, then with a crust 25 miles thick it would require the globe to have contracted 42 miles before you would get sufficient matter to make up the amount of mountain measured above the sea-level and their roots."

Captain C. E. Dutton thinks that Mr. Fisher has touched too briefly upon another argument against the contraction hypothesis, namely, that the features to be explained are not such as would have been produced by contraction.[2] "The strains set up in the crust by a shrinking nucleus would be such that for any given amount of corrugation with the axes (of the folds) in one direction, there must be an equal amount with the axes at right angles to that direction. The localization of mountain chains and plications in long narrow belts, with the axes of the folds all approximately parallel, and with no corresponding plications at right angles to them, is an impossible result of a collapsing spherical shell." In other words, if the features were caused by contraction, there would be a network of small mountain chains all over the earth's surface, like

[1] Op. cit. p. 170.

[2] "American Journ. of Science," vol. xxiii. p. 283.

the wrinkles on the skin of a dried apple; they would not be nearly so long or so lofty as they are.

Hypothesis of Columnar Expansion.—If compression has not been caused by contraction, it can only be due to some kind of expansion or extension of the earth's crust, and Mr. Fisher suggests that this is to be found in the production of fissures opening upwards from the liquid substratum, and filled with matter proceeding from it. Considering the amount of water which is always given off as steam during volcanic eruptions, he believes the liquid magma to contain a large amount of water-substance (dissolved in the state of gas), and thinks that all fissures originating on the under surface of the crust would be immediately filled with this gas, under a pressure of about 10,066 tons to the square foot; the gas would consequently exert this pressure in widening the fissure, that is to say, in compressing the rocks on either side of it. "When the rent reached the surface, the vapour would rush forth, and be followed by the magma itself, now appearing as lava, and thus a volcano would be formed; but this would be an exceptional occurrence. It would be only here and there that the vapour would escape at the surface, because its doing so at one point would relieve the internal pressure for a long distance."[1] The fissures are kept open and the lateral compression maintained by the injection of the molten material, which solidifies and adds to the mass of the crust, the upper ends of such injected fissures appearing on exposure as dykes of igneous rock.

Mr. Fisher also considers the consequences which would ensue from the compression of a crust resting upon a fluid substratum, and shows that for every subaerial elevation above the mean surface there must be a corresponding protuberance dipping downwards into the fluid below, and, owing to the lower parts being softened by heat, a greater thickness will be sheared downwards than upwards. Assuming that under lateral compression two-fifths of the thickened part would go up and three-fifths would go down, and that the ratio between the specific gravities of crust and substratum is the same as that between those of

[1] "Physics of the Earth's Crust," pp. 186, 284.

granite and basalt, which is nearly as that of ice to water, he shows that the thickened tract would sag still further downwards.[1] "Hence depressions would arise on both sides of the ridge, and the ocean, which covers the general surface, would be deeper than elsewhere along two channels parallel to and at some little distance from the ridge. But should the ridge be steeper on one side than on the other, as seems inevitable, the ocean would be deeper on the steeper side." This relation between ocean depths and mountain chains seems actually to exist, as already mentioned.

Lastly, he considers the consequences of the transference

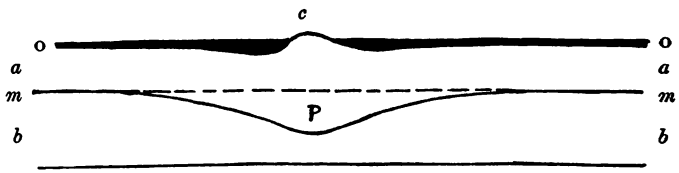


Fig. 150. Diagram to show the Roots of a Mountain Chain.

a, Crust. *b*, Substratum. *c*, Mountain chain. P, Downward protuberance. o, o, Ocean level. *m*, *m*, Lower mean level of the earth's crust.

of sediment from the mountain chains to the oceans, and shows that on hydrostatic principles the areas from which matter is removed will rise, while the areas to which sediment is transported, being loaded, will sink.

Hence he concludes that the vertical movements affecting the earth's surface are of two kinds; one resulting from compression, the other from the laws of hydrostatic equilibrium simply. As the result of the latter degradation and elevation are necessarily correlatives of each other; the degradation of the tract causes more rock to rise up, to be in its turn degraded and removed.[2]

[1] Op. cit. pp. 131, 278.
[2] Op. cit. p. 224.

CHAPTER II.

EARTH-SCULPTURE, OR THE EVOLUTION OF SURFACE-FEATURES BY THE PROCESS OF EROSION.

IN Part I., Chapters VI., VII., VIII., we described the action of the various agencies which are continually engaged in the work of erosion and denudation; but their operations were treated rather from a detritive point of view, as resulting in the collection of materials for the formation of new rocks, than as leading to the exposure of new surfaces, or the production of new forms on previously existing surfaces.

It is clear, however, that agencies which sweep away so much rock from the land must in time cause very great changes in its physical features. An elevated table-land, for instance, by the unequal disintegration of its surface, and by the erosion of valleys out of its mass, may gradually be converted into a series of hill ranges more or less isolated from one another. Such a process is fitly termed *Land-sculpture*, as analogous to the work of a sculptor, who carves effigies out of solid blocks of stone.

Many persons express surprise that the formation of such prominent features as lofty hills and profound valleys should be attributed to such comparatively feeble agencies as those above mentioned; but it must be borne in mind that we are naturally apt to underrate the amount of work done by these erosive agencies, because we see that in any period of time during which we can observe their action the results produced are very small. On the other hand, when we look at the magnitude of the results which have been produced in past time, we are liable to suppose that the agencies which have operated in former times were much more powerful and destructive than those which are now in action around us. "When, however, we come to reason on the matter, we find it very difficult to imagine

what these agencies could have been if they were altogether different from 'existing causes;' and equally difficult to suppose that existing agencies have ever acted with much greater intensity than at present, unless we assume the general physical laws of the world to have been different from what they are now" (Jukes).

We shall therefore take it for granted, in accordance with the tenets of the Lyellian philosophy, that all the geological phenomena observable among stratified rocks are due to the same causes as those now acting in some part of the world, or to some modification and combination of these causes, such as we may reasonably suppose to have occurred in the course of the earth's history.

To such seemingly insignificant and slowly acting causes, operating continually through long periods of time, must be attributed all the erosion of rock which gives to elevated land its cliffs and precipices, its hills and valleys, and all the varied features of the earth's surface.

Share taken by different Agencies.—The detritive and erosive agencies already described may be grouped under two heads, according to differences in their mode of operation, and in the results of their action.

1. Marine agencies, which act along the margin of the land, and tend to produce an approximate level surface or plain.

2. Subaerial agencies, which act over the whole surface of the land, and tend to produce a system of valleys and watersheds, hollows and relative eminences.

No part of the sea bottom could be raised into dry land without passing through the destructive plane of the sea level, neither could any part of the land be depressed without passing through the same plane, and being exposed for a shorter or longer period to the erosive action of the waves. These agents would wear down the inequalities of its surface and would produce an inclined plane, the extent and inclination of which would depend on the slope of the sinking or rising land, and the rate at which the movement took place. It must be remembered, too, that a tract of land which has been submerged and then upraised must have been twice subjected to this levelling process, and on its second emergence would present a wide area with a

nearly level or slightly undulating surface. Such an area has been termed a *plain of marine denudation*, but would perhaps be more aptly called a *surface of planation*. When once any such tract had been brought almost up to the sea-level, only a very slight further uplift would be required to raise a large area of it through that level, and cause it to become dry land, so that there would be no time or opportunity for the formation of cliffs. Slight irregularities there doubtless would be, and indeed it must be understood that the words *plain* and *planation* are used in a general sense to convey the idea of a surface, where the vertical height of any inequality is small, as compared with the horizontal extent of the area.

As soon as this surface produced by marine erosion is elevated into dry land, it is subjected to the detritive action of the subaerial agencies already described, and is ultimately carved out into new forms of hill and valley. In the present chapter we propose to describe some of the more striking forms and features which are developed in this process of rock-sculpture. The arrangement of the hills, ridges, and valley, in any given case, will depend partly on the original inclination of the surface of planation, and partly on the nature and structure of the rocks composing it.

Conditions which determine the Position of Hills and Valleys.—The initial courses of the streams, and the general contour of the ground, will depend on the following circumstances :—

1. The original slope of the surface.
2. The disposition and lie of the stratified beds.
3. The relative resistant power of the rocks, depending partly on their hardness, and partly on their chemical composition.
4. The presence or absence of igneous rocks.
5. The direction of any strong divisional planes, such as those of bedding, jointing, cleavage, or faults.

Of these conditions, the second is perhaps the most important, so much depending upon whether the beds are horizontal, inclined, or curved, that it will be instructive to consider each of these three cases separately.

A. *Erosion of Horizontal Strata.*—The simplest case which

can be imagined is that of the elevation of broad and level tracts of country, in which the strata are for the most part nearly horizontal. In such a case, the greater part of the surface would be occupied by one or two kinds of rock, and the resultant features would depend chiefly upon the manner in which these crumbled down under the action of erosive agencies. Fig. 151 illustrates the forms into which horizontal strata of sandstone, shale, and limestone may be carved. The sandstone which formed the original surface, S P, has been cut through, and portions only are left to form the flat-topped ridges or *mesas* which separate the valleys. These valleys will be wide, with long gentle slopes where the sides consist of clay, but will have a narrow gorge or cañon at the bottom, if the stream has trenched the underlying limestone.

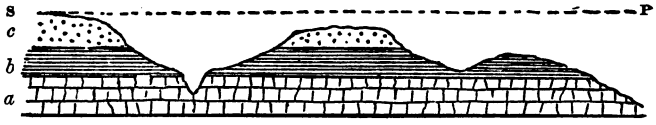


Fig. 151. Erosion of horizontal Beds.
a, Limestone. *b*, Shale. *c*, Sandstone.

Such cases are rare in Europe, but excellent instances are to be found in eastern Egypt and in the western and central parts of North America. The forms produced by the action of rain and wind upon the horizontal strata of these regions, and the excavation of profound ravines or cañons by the rivers which traverse them, have already been described; but the combined effect of all the different detritive and erosive agents in Colorado and Utah is to produce an amount of sculpturing and a diversity of outline which is truly wonderful. Dr. Geikie has given an excellent picture of the peculiar scenery of the Uintah Mountains in the following terms:[2]—

"The world can show few more impressive memorials of the efficacy of subaerial erosion than the Uintah Mountains. There are no structureless crystalline rocks here to deceive us

[1] "Geological Sketches," Macmillan, 1882, p. 229.

with their ruggedness. Wherever the eye turns it detects the same long lines of horizontal stratification that serve as a base from which the reality and amount of the erosion may be measured. . . . Originally the rocks stretched in an unbroken sheet across the mountains; but in the course of ages this continuous mantle has been enormously eroded. Deep and wide valleys, vast amphitheatres, lofty terraced alcoves, and profound gorges, fretted with an infinite array of peaks, buttresses, pinnacles, columns, obelisks, and endless forms which defy the observer to find properly descriptive names for them, have gradually been carved out of these rocks. To gain such a vivid impression of the importance of subaerial waste in the evolution of mountain forms was worth all the long journey in itself." Views and descriptions of this scenery will be found in Captain Dutton's "History of the Cañon Region of Colorado" (U.S. Survey Monograph).

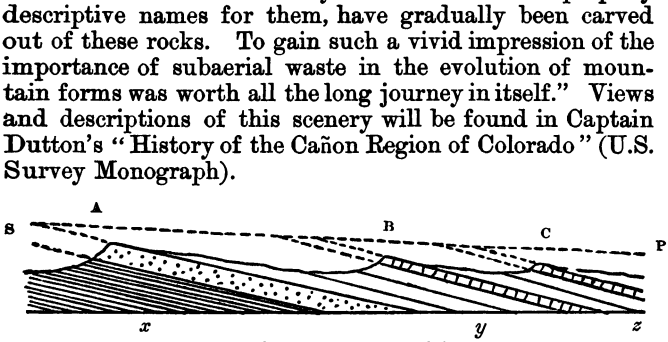


Fig. 152. Erosion of inclined Strata.

B. *Erosion of Inclined Strata.*—Next let us suppose the case of a slightly inclined area of planation, consisting of different strata dipping constantly in one direction, so that their outcropping edges form broad bands stretching across the surface. In this case the surface features developed by denudation will depend upon the comparative destructibility of the different rocks. Where hard and soft beds alternate with one another, as so frequently happens, the softer bands will be worn away more rapidly than the harder, and the surface will be sculptured into a series of alternate ridges and hollows, with long gentle slopes in the direction of the dip, and steeper slopes across the outcrop of the hard beds. These steep slopes are called *escarpments*, and their general direction coincides with that of the strike. In fig. 152, S P is the original surface of planation, and A B C are the escarpments

gradually developed by the detrition of the softer bands of rock, *x y z*. The broken lines show the original prolongation of the beds, and the extent to which the escarpments have receded.

The way in which these peculiar and characteristic features are developed, appears to be as follows:—The first lines of drainage established on the area of planation would form transverse valleys across the slope, from S to P, with longitudinal tributaries along the strike of the beds. The streams in the former would cut through hard and soft beds alike, down to a certain base level of erosion, and the depth of their valley in the soft beds would necessarily depend on the depth of the ravines which they could

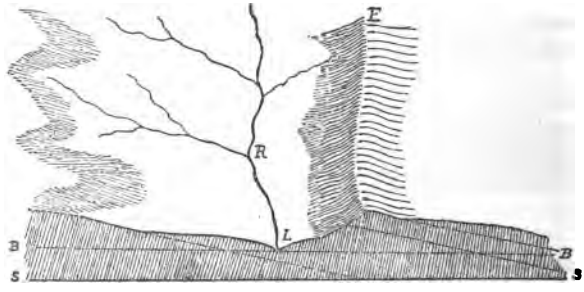


Fig. 153. Formation of Escarpment.

excavate through the hard beds. In the tributary valleys the soft beds would be rapidly eroded, but the streams could not excavate the valleys deeper than the level of the point where they join the main river; each tributary, therefore, will have its base line of erosion limited by the depth of the main valley, and when the limit of vertical erosion has been reached, the stream will be chiefly occupied in carrying off the material washed into it by the rain, and the valley will increase in width by lateral erosion.

The formation of the two slopes, one long and gentle, the other short and steep, depend on the position of the base line of erosion at the junction of the tributary with

the main stream. As the main river gradually deepens its channel, the tributary will continually shift its debouchure nearer and nearer the base of the escarpment until it has attained the position indicated in the diagram, fig. 153. The lower part of this figure represents a section along the channel of a transverse valley, cutting through the escarpment E, formed by a hard bed, the line, B B, indicating the bottom of the valley, and the course of the main river: the upper part of the figure is a plan of the tributary valley with its stream, R L, which has cut down to the lowest limit of erosion at its debouchure, L. It will be seen that to do this it has eroded one side more rapidly than the other, and has produced the special features of the two slopes. The features thus commenced at the debouchure of the tributary valley are gradually carried back along the strike of the beds as the process of detrition is continued.

It sometimes happens that the sloping upper surface of a hard, durable bed is completely denuded of its covering by the atmospheric agencies, so that the slope of the ground coincides for some distance with the sloping surface of the inclined stratum, see fig. 152. Such a surface is called a *dip slope*, while the opposite slope may be termed the *scarp slope*.

Recession of Escarpments.—An escarpment once produced in the manner above described will be continually modified, and made to recede by the unceasing action of the subaerial agencies which are effecting the detrition of the whole country. Rain, frost, and springs cause a constant succession of landslips along the scarp slope, and every mass of rock thus detached is gradually disintegrated and crumbled in earth, which is eventually washed away by the rain into brooks and streams.

Thus the scarp edge is gradually carried farther and farther back in the direction of the dip, and its outline depends partly upon the relative share taken by the agencies above mentioned, and partly on the inclination of the strata by which it is formed. Sometimes an escarpment forms a continuous and uninterrupted ridge, running in a nearly straight line for a considerable distance; sometimes its edge is furrowed by transverse valleys, and hollowed

out into a succession of deep embayments, with intervening spurs and promontories that form more or less isolated hills.

The sinuosity of its outline generally depends upon the presence or absence of strong springs, and the extent to which they can cut their way back through the escarpment. This difference is well illustrated by the two great escarpments which run through Lincolnshire. Of these, the more westerly is known as the "Lincolnshire cliff," and forms a remarkably straight ridge, running nearly due north and south from Lincoln to the Humber, with very few sinuosities, and with little variation in height. This ridge is formed by the outcrop of the upper part of the series of clays and marlstones, called the Lias, capped by the lower beds of the Lincolnshire limestone; the easterly dip of the beds, and the slight thickness of the limestone along the top of the ridge, prevent the existence of strong or numerous springs along its western slope, and the only great gap or transverse valley is that through which the Witham runs at Lincoln. The easterly escarpment is that of the Chalk Wolds, which runs in an irregular line from S.E. to N.W., and consists of (1) a series of stiff clays and ironstones, succeeded by (2) coarse sand-rock and (3) red chalk, surmounted by (4) greyish-white chalk. The dip is very slight, and the thickness of chalk is considerable, so that strong springs are thrown out sometimes at the base of the chalk, sometimes at the base of the sand. The action of these springs has produced beautiful little hollows and recesses in the face of the scarp, some of which have been widened and extended into valleys by the rain-water draining into them from the higher ground. The edge of the Wold escarpment has consequently acquired a most irregular and diversified outline, which forms a remarkable contrast to that of the Lincolnshire cliff.

c. *Erosion of Curved Beds.*—We have next to consider the case of an area of curved or undulating beds, and the influence which such curvature exercises upon the development of its physical features.

Let the fig. 154 represent a section through such an area, and let us suppose the rocks to consist of shales and sandstones overlying limestones, and thrown into anticlinal and

synclinal curves. The features usually presented by the detrition and sculpture of such an area are those indicated in the figure, namely, a series of alternate ridges and valleys, with nearly equal slopes. Usually, moreover, they have, this peculiarity, that the valleys coincide with the anticlinals, and the hills with the synclinals, so that the stratigraphical troughs become orographical ridges, and *vice versâ*, which is the opposite of what might, at first sight, be deemed probable. This arrangement, however, is the natural result of the structural peculiarities imparted to the rocks by curvature, and the consequent increase or decrease of their liability to mechanical erosion. Where the strata have been thrown into sharp curves and contortions, they have generally been more or less compacted and indurated; but where they are bent into broad anticlinals,

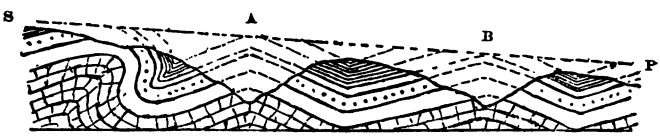


Fig. 154. Erosion of curved Beds.
S, P, Surface of Planation. A, B, Valleys coinciding with Anticlinals.

their coherence is weakened, because they have been subjected to tension; and, lastly, in the synclinals, they have been subjected to compression, and consequently their coherence is increased.

Thus, when the first stream courses were established over such an area, the main rivers would flow from S towards P, and the indurated rocks near S would remain as high ground. Of the tributary streams, running more or less along the strike of the beds, some would flow along the anticlinal axes, and some perhaps along the synclinal axes; let us consider which of these would be likely to excavate the deepest channels. It must be remembered (see p. 79) that where rocks are freely jointed they yield more easily along these planes than along those of bedding. Now the principal effect of tension on the rocks of the anticlinals would be to open the lines of jointing; consequently, as the stream undermined the bases of the blocks, they

would slip down on both sides along the joint planes, and falling into the stream would be broken up and carried away. In the synclinals, on the other hand, the effect of compression would be to close up the joints; and, moreover, these planes being mostly vertical to the stratification, would incline away from the banks of the stream, so that the beds would not be so liable to break up or slip down.

The drainage, therefore, will eventually be directed into the deeper channels running along the anticlinal axes, and the widening of these valleys by pluvial action will leave the synclinal axes to form ridges and ranges of hills. By a similar process of circumdenudation a *periclinal* basin will become an isolated hill.

Influence of relative resistant Power.—The relation above described as ordinarily subsisting between the flexures of the strata and the surface features of the ground holds good only when the rocks which formed the original surface of planation did not differ very greatly in their resistant power. If, however, some of them possessed greater inherent powers of resisting disintegration and detrition than their neighbours, the latter will be worn away, and the former will remain as hills, whether this result is or is not favoured by the general arrangement of the flexures. The whole process, in fact, is one of natural selection, and the development of surface inequalities out of any tract of country may be described as the result of selective and differential erosion, the power of the destructive agents being directed and modified by the capacity of the different rocks to resist them,—the softer and weaker portions of the surface being continually attacked and destroyed, while the harder and more durable portions survive the detrition and maintain their position for a longer period of time. The law of the survival of the strongest and fittest holds good, therefore, in physiography as well as in biology, in the development of mountains as well as in the development of species.

Many instances of the coincidences of the hill-ranges with anticlinal axes, when these are formed of hard arenaceous rocks, are to be found in the south of Ireland: the Commeragh, Knockmealdown, Galtee, and Macgillicuddy ranges, and the

higher mountains of Kerry, Cork, and Waterford generally.[1] In these counties the hills are formed of anticlinal folds of red sandstones and slates, while the valleys lie in synclinal curves of shales or limestones. Northward, however, the sandstones become thinner, and another set of older slates and grits emerge from beneath them and form the central heights of the Keeper group in Tipperary. In the same way masses of hard igneous or metamorphic rocks elsewhere form high ground, because they consist of more durable material than the surrounding strata. Dartmoor consists of granite, the Malvern Hills of hornblendic gneiss, and Snowdon is chiefly built up of thick felpsathic lavas and ashes.

On the other hand, valleys may coincide with synclinal axes, when these are occupied with beds which yield easily to chemical disintegration or mechanical erosion. In the counties of Cork and Waterford, for instance, the valleys are excavated along the shales or limestones which occupy the synclinal axes. The limestones have been worn away, in spite of their hardness, because they yield to chemical action and their material is removed in solution as well as in suspension.

Other cases where valleys coincide with synclines may have arisen from the fact that on the original surface of planation, the synclinal axes were occupied by limestones, and the valleys excavated along these axes may sometimes have still been maintained as lines of drainage after the removal of all the limestone in them.

It is also worthy of note that the stratigraphical position of limestones exercises a most important influence on the manner in which they yield to detritive agencies. Thus, in a series of inclined beds (fig. 152), limestones interstratified with clays behave as hard rocks and form escarpments, because they are greatly protected from the chemical action of rain by the impervious covering of clay above them; in a series of curved beds, however, they behave as soft rocks, and form low ground (see fig. 154), because they are exposed to such chemical action, and, even under the unfavourable conditions of a synclinal, the combined forces of chemical and mechanical erosion are able to work faster than the

[1] See "Explanations of the Sheets of the Geol. Survey of Ireland."

latter agencies alone can, even when they are favoured by the conditions of an anticlinal.

Connection of Valleys with Lines of Fault.—Since the process of earth-sculpture is one of selective erosion, and the detritive agents always seize upon lines of inherent weakness, it is not surprising that valleys should sometimes coincide with lines of fault. So, also, among rocks which are well jointed, like limestones, valleys often coincide with the direction of the master-joints. The streams descending from the original watershed will naturally follow the lines of least resistance, and therefore the direction of transverse valleys may sometimes be determined by master-joints or by lines of fault. Similarly, in districts where there is no very great difference in the comparative destructibility of the rocks, the course of the tributary valleys may be guided by any lines of weakness which exist.

It is quite a mistake, however, to imagine that faults gave rise to gaping fissures which were subsequently widened into valleys by the action of streams, or to suppose that most valleys have been originated by faults because some happen to coincide with such lines of fissure. Cross-faults produce no feature at the surface of the ground, and strike-faults only do so when they bring yielding and durable rocks into apposition; such a feature is due to what may be called differential detrition, and is not produced by the throw of the fault; a valley may or may not coincide with a strike-fault under such circumstances, but if it should do so, its direction has been determined by the presence of the yielding rock, and not directly by the line of fault. Even if mural features were produced at the time of faulting (see p. 44), they would in most climates be rapidly worn down and destroyed, except under the conditions above mentioned.

The inlets of a rocky coast are often due to the presence of such fissures, whether faults or joint-planes, along which the waves have worked their way more rapidly than elsewhere (see p. 119), but no one supposes that the width of the inlets bears any relation to the space between the walls of the fault or joint, or that all inlets have been formed in this manner because a few owe their origin to such lines of weakness. The relative destructibility of the rocks, and

the disposition of the strata, are far more important and more general causes of differential erosion and consequently of the formation of valleys.

Breaching of Escarpments and Hill Ranges by Rivers.—It is a remarkable fact, of which England furnishes many examples, that rivers sometimes continue a direct course through a line of escarpment, when we should have expected them to have been deflected either to one side or the other along the base of the escarpment. In other cases, a river, after running for many miles along a well-marked valley, suddenly turns at right angles and passes by a deep and narrow ravine through one of the bounding ranges of hills. After the descriptions given of the manner in which parallel ranges of hills and valleys have been produced, the origin of these gaps or ravines through hills and escarpments will be easily understood; the simple fact being that the hills or escarpments did not exist when the river, which now flows through them, first began to excavate its channel. The course of the primary transverse river was determined by the slope of the original surface of planation, and it has continued to occupy the same channel during the whole process of erosion by which the longitudinal valleys were formed and the ridges developed.

This explanation was first proposed by Mr. Jukes to account for the courses of some of the rivers in the south of Ireland, and the following is condensed from his description of the valley of the Blackwater, which he selected as an illustration. "The parts of the counties of Cork and Waterford which are here adjacent to each other consist of a number of alternate ridges and valleys, which run with great regularity almost exactly east and west for fifty or sixty miles. The hills are formed of anticlinal folds of red sandstones and slates, while the valleys are occupied by synclinal curves of thick grey limestone. The loftiest hills of the district are the Knockmealdown mountains, which rise to 2,600 feet above the sea. The lower parallel range on the south is known as the Drum ridge, and between these two ranges lies the limestone valley of Lismore, which forms a well-marked trough, both externally and internally. It runs in from Dungarvan Bay to Fermoy, a

distance of forty miles, and a road might be taken the whole of that distance without ever passing over ground much more than 100 feet above the sea.

"The Blackwater river, rising in Kerry, runs for fifty miles down to Fermoy, and continues in the same straight line down the Lismore valley for about twenty miles farther, to the little town of Cappoquin.

"There, however, the river suddenly turns at right angles to its former course, and instead of following the regular east and west valley, which continues straight out to the sea at Dungarvan Bay, it cuts through the high land of the Drum ridges due south to Youghal Bay, which is, moreover, five miles farther from Cappoquin than Dungarvan Bay. Why does it take this extraordinary course? Because just to the northward of the bend are the Knockmealdown mountains, and the original river ran due south from near their summits down the slope of the original surface towards the sea. This little transverse river would be likely to receive a large rainfall, and would certainly have the most rapid course; it would, therefore, be able to keep open its original channel through the sandstone ridge while the surface of the limestone districts was sinking into longitudinal valleys, and the tributary streams were gradually increasing in length. It is evident that to whatever extent these longitudinal valleys might proceed, their streams could never cross the original transverse valley formed by the primary river. The Blackwater, as it is above Cappoquin, is one of these tributaries, but it has never crossed the primary river so as to continue down the remainder of the longitudinal valley to Dungarvan Bay, and could never do so unless something happened to cut a channel lower down that remaining part of the valley deeper than the channel already cut down to Youghal Bay."

In this, and other cases, the primary or transverse valleys are due, in the first instance, to the comparative steepness of the slope of the original flanks of the mountain chain, giving an impetus to the streams, so that channels would be worn directly across all the bands of rock that run parallel to the length of the chain, independently of their hardness or softness.

No stream could cut its channel in any soft band in the higher part of its course below the level of the channel in the next hard band of the lower part of its course. Its channel, however, would naturally be more narrow, and its sides more steep and precipitous, in the parts where it cut across a hard band than where it traversed a soft one. The softer and more easily eroded banks of the stream would always be apt to slide down the slopes, and the valley would widen there accordingly. Moreover, the longitudinal valleys, originating in these soft or easily destructible bands, would be wider and more regular than the lateral valleys, and if a soft band was very wide, and continued for many miles along the length of the chain, it is quite possible that the longitudinal valley formed in it, although originally a mere tributary to the lateral valley, and caused by a stream commencing to drain into that valley, might ultimately be worn back along the soft band, so as to be not only wider but far longer than the upper part of the primary valley which lies above the junction of the two. Such a longitudinal valley would be likely to bring a greater volume of water from a greater distance than the upper part of the lateral valley itself might bring. In such cases the stream running down this longitudinal valley would be very likely to be considered the main stream, although it was originally a mere tributary of the transverse valley.

The Wealden area of Kent and Sussex furnishes another excellent illustration. The structure of this district is that of a broad anticlinal curve, the arch of which has been destroyed and carried away by erosion, so that the central area now consists of a ridge surrounded by tracts of low ground which are bordered on the north, west, and south by double escarpments of chalk and greensand. Eastward, however, there is no barrier, and the coast between Eastbourne and Folkestone is low and flat, so that we should naturally expect to find the chief rivers running eastward and having their outlets along this coast. But instead of this being the case, the principal rivers rise in the central watershed, and flow north and south, escaping to the sea through narrow valleys which breach the great chalk escarpments known as the North and South Downs. The

student should not fail to inspect the geological model of the Weald exhibited in the Museum of Practical Geology (Jermyn Street).

The only explanation of these facts is a repetition of that already given: marine erosion first produced a surface of planation across the whole district while it was being slowly elevated, so that this original surface sloped gently from a central line towards the north and south. The primary streams naturally followed these slopes from the central watershed, cutting across soft and hard beds alike, and forming the transverse valleys. Their tributaries formed longitudinal valleys opening into these transverse channels, and the streams have never departed from the courses thus established upon the original surface. Thus, throughout the whole process of subsequent erosion and denudation, the Medway, the Mole, and the Wey have gradually excavated and kept open the transverse passages through the North Downs; while the Arun, the Adur, and the Ouse have in the same way formed the valleys which traverse the South Downs.

Even the highest mountain chains in the world are breached by transverse valleys which appear to have been entirely excavated by river-erosion. Dr. Emil Tietze[1] has expressed the opinion that in many such cases the river which traverses the mountain chain takes its rise in a district which was dry land during the time the rocks of the chain were being deposited. The upper part of the river-course is then older than the mountain-range, and, as the rocks of the range were slowly raised out of the water, the river prolonged its course over the land thus formed, cutting its channel deeper and deeper as the range became higher and higher. In this way he explains the transverse valleys which are cut across some of the highest ridges of the Elburz mountains in Persia; and believes that the gorges of the Indus and Brahmapootra through the Himalayas have been formed in the same way. These rivers take their rise on the slopes of the Karakorum and Kuenlun ranges, both of which are far older than the Himalayas; the rivers which flowed off them would extend themselves

[1] "Jahrbuch der kais.-kön. geol. Reichsanstalt. Vienna," xxviii. p. 581. See "Geol. Record" for 1878, p. 197.

southward when upheaval began, and cut valleys through the Himalayan rocks as the latter slowly rose into mountains.

Formation of Drainage Basins.—A basin of drainage is a district within which all the streams drain towards one main artery or central river. The dry land may then be parcelled out into separate basins of drainage divided from each other by "watersheds," or ridges from which the rain-water runs in different directions, as it does from the ridge of a house-roof.

The rain-water that falls upon the surface of the basin of drainage is disposed of in three ways (see p. 68); such of it as flows over the surface of the ground, or is thrown out from springs, gathers into little brooks and rivulets; the union of these form larger streams, and the confluence of many such streams creates a river. A river is large in proportion to the extent of the catchment area and the amount of the rainfall upon that area.

A basin of drainage, then, and its resulting river, are developed by a regular systematic operation, and the process is exemplified to a certain extent by the drainage of a mud flat at low tide, which has been graphically described as follows:[1] "If we watch the tide receding from a flat muddy coast, we see that the mud flat, even where no fresh water drains over it from the land, is frequently traversed by a number of little branching systems of channels, opening one into the other, and tending to one general embouchure on the margin of the mud flat, at low-water mark. The surface of the mud is not a geometrical plane, but slightly undulating; and the sea, as it recedes, carries off some of the lighter and looser surface-matter from some parts, thus making additional hollows, and forming and giving directions to currents, which acquire more and more force, and are drawn into narrower limits as the water falls. Deeper channels are thus eroded, and canals supplied for the drainage of the whole surface. First two, and then more, of these little systems of drainage unite, until at dead low-water we often have the miniature representation of the river system of a great

[1] Jukes, "Manual of Geology," second edition, p. 105.

continent (wanting, of course, the mountain chains) produced before our eyes in the course of a single tide, in the very manner and by the very agent by which all river systems on all islands and continents have been produced. The difference between them is this only, that our islands and continents are now above the sea, not in consequence of the gradual fall of the water, but in consequence of the gradual rise of the land."

Let us suppose a land commencing to rise above the sea, the ridge of a mountain chain, or that which afterwards becomes or discloses a mountain chain, being the first part to become dry land. As soon as this tract of dry land is established above the reach of the waves, rain and rivers commence their work of erosion and excavation, beginning first upon the ridge, and extending to each piece of lower ground as it is laid dry. It is easy to see that the first rain streams formed on the rising ridge would run directly off down the slopes from the crest into the sea. These would begin to form the transverse valleys of the chain. As soon as they became a little deep, other small streams would flow into them from their sides; and these, acting on any softer or more easily destructible bands of rock, would begin to excavate tributary valleys which would extend themselves laterally on either side of the primary or transverse valley, and would receive the drainage of a certain section of the mountain region.

If the rainfall was everywhere the same, if the mountains consisted of only one kind of rock, and if this rock was composed of a succession of horizontal beds, the resulting system of rivers and watersheds would be very symmetrical; but since all mountain ranges consist of many different kinds of rocks, the beds of which are tilted in different directions, and the rainfall varies at different places, it follows that some streams are able to work more rapidly than others, and so the relative areas of the drainage basins come to be very unequal.

The various conditions which determine the courses of rivers have been discussed in the preceding pages; and when once they have selected their channels, they deepen and extend them in the manner described, except in the

few instances where the subsequent extension of one stream has caused the diversion of another.

Under ordinary circumstances, the valleys once formed are not obliterated by any concomitant changes, but exist as long as the hills remain from which the streams descend, and they are continually enlarged, either vertically or horizontally, by the action of the rivers that run through them, and the rain-water which runs into them.

CHAPTER III.

PROOFS OF THE AMOUNT OF MATERIAL REMOVED FROM EXISTING SURFACES.

IN this chapter we shall consider some geological features which furnish absolute proof of the enormous amount of detrition and denudation that has taken place in some parts of the country; these considerations will enable us to realize what vast thicknesses of rock have in many cases been removed during the process of erosion, which has led to the development of the present physical features of the country. They may be treated conveniently under the following heads:—1, evidence from the outcrop of strata; 2, from faults; 3, from outliers and inliers; 4, from mountains of upheaval.

1. *Outcrop of Beds.*—Where a series of beds dip one beneath another, as in fig. 152, over a considerable breadth of ground, it is clear that they cannot have originally terminated in that manner, for it is the very fact of their abrupt truncation that causes them to crop out on the present surface. The higher beds must originally have extended for long distances beyond their present lines of outcrop, and a very great thickness of rock must once have existed above the present surface.

To take an instance which has already been partially described, namely, the south-east part of Ireland, see figs. 122 and 123. There is reason to believe that the coal-measures, which now only occur as isolated patches, had originally a very wide extension over this part of the country, overspreading and overlapping the Carboniferous limestone, as shown in fig. 125. So great, however, has been the loss of material during the process of detrition and denudation by which the present physical features have been produced, that not only have the coal-measures

been removed from the greater part of the country, but the erosion has in many places extended through the whole thickness of the Carboniferous limestone, and has cut deeply into the Old Red Sandstone below.

In some places the erosion has extended even to the bottom of this division, so as to re-expose the old denuded surface of the Silurian rocks upon which the sandstones were deposited. But it has gone even further still, for in some localities, as at Freagh Hill and along the northern slope of the Galtee Mountains, it has worn deep hollows and valleys in the Silurian rocks themselves, several hundred feet below that surface on which the Old Red Sandstone was deposited. From the extent of this denudation,

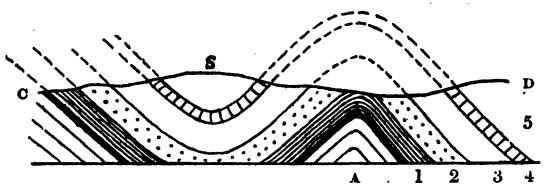


Fig. 155. Thickness of Rock removed by Denudation.

therefore, it can be proved that a thickness of between 5,000 and 6,000 feet of rock has been removed from some parts of the district.

The time required for the removal of such enormous masses of rock must have been very great; and equal volumes of rock must at the same time have been deposited elsewhere, because detrition and deposition are coordinate terms, one being the measure of the other. Accordingly, in Antrim and other parts of Ireland we find some of the deposits which were formed out of the materials supplied by the detrition of these older rocks.

Where a surface has been formed across anticlinal and synclinal folds, the outcrops of the different beds supply a means of actually estimating the minimum thickness of rock which has been removed since the folds were formed. Thus, in fig. 155, the distance between C and D may be several miles, and the thickness of the beds, 2, 3, 4, 5, may

be respectively 100, 200, 400, and 200 feet. It is clear that all these beds must originally have been continued over the anticlinal, A, or they could not have been brought into the synclinal trough, S. The minimum thickness of rock, therefore, which has been removed from the surface over the point, A, must be 900 feet; and if any more beds came in with the same dip beyond D, their thickness would have to be added to this amount.

Fig. 145, p. 435, illustrates an actual case in which this estimate may be made; if the thickness of the slates between B and D be 5,000 feet, it is clear that a depth of rock of more than that thickness must have been removed from the top of the anticlinal fold, B, and, further, the same thickness of rock must once have extended across the Menai Straits, and all over Anglesea, unless the strata thinned in that direction. That much of it really did so extend is proved by some of the beds being brought in here and there by faults and synclinal curves.

In the same way Sir A. Ramsay has shown that in some parts of South Wales a thickness of at least 11,000 feet of rock has been removed from the present surface of the country.[1]

2. *Faults.*—Equally convincing is the evidence furnished by the great dislocations or faults which traverse every country. Some of these are vertical displacements to the amount of several thousand feet (see p. 364), and yet they seldom produce any effect on the surface of the ground. To take an extreme case as an illustration, there is a fault traversing the Appalachian Mountains in North America, which has a vertical throw of 20,000 feet, and yet the surface is so planed down that a man can stride across the line of fault, with one foot on a bed which was originally[2] 20,000 feet above that on which the other foot rests. Again, many of the maps of the "Geological Survey of Great Britain," especially those of the coalfields, show so many faults that they are covered with a net-work of white lines. These faults are of various magnitudes, from a few feet to many hundred, and yet no sign of such displace-

[1] "On the Denudation of South Wales," Mem. Geol. Survey, vol. i. p. 297.

[2] Campbell, "Frost and Fire," chap. li.

ments is visible at the surface, which may be a continuous tract of undulating fields and meadows. In all these cases it is clear that a thickness of rock equal to the maximum amount of vertical displacement has been removed from the surface of the country.

3. *Outliers and Inliers.*—An outlier is, as the name implies, an outlying or isolated portion of a bed, which has been separated from the main mass with which it was originally connected by erosion and denudation, just as an island is separated from the mainland (see fig. 122, p. 381, where outliers of Old Red Sandstone are shown).

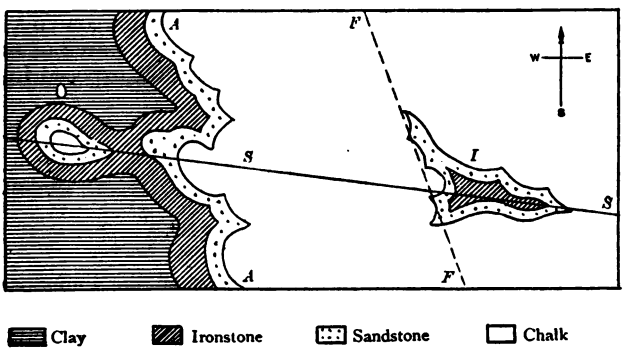


Fig. 156. Plan of Outlier and Inlier.

The simplest form of an outlier is that which so often occurs in connection with a line of escarpment, the unequal recession of which has left a series of bays, promontories, and outliers. It is easy to see how the neck of a promontory may be gradually worn through by the action of rain and springs until it is converted into an isolated hill, the very existence of such a hill becoming a proof of the former extension of the beds, and of the recession of the escarpment.

Very frequently the existence of the promontory and subsequent outlier is due to a slight synclinal curvature of the beds, the inward dip giving them a greater power of resistance to detritive agencies, and diminishing the liability to landslips. So often is this the case that the very occur-

rence of an outlier affords strong presumptive evidence of this inward dip, although the actual inclination of the beds may be so slight as to be inappreciable in a quarry.

Conversely, an anticlinal curvature, when denuded, often gives rise to what is called an inlier, which may be defined as the isolated exposure of an underlying bed amidst others which are geologically above it.

Figs. 156 and 157 are respectively a plan and section illustrating the occurrence of an outlier and an inlier. A A is an escarpment formed by successive beds of sandstone, shale, and limestone; o is an outlier of the limestone and shale, resting on a promontory of the sandstone, which is still connected with the main mass by a narrow neck. I is an inlier of the sandstone, within an inlying area of the shale, brought up by an anticlinal curve, and exposed in a

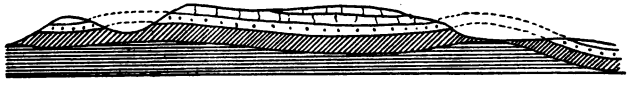


Fig. 157. Section along line s s.

valley excavated out of the long slope of the limestone. The section is taken along the line, s s, and illustrates the relations of the external features to the internal structure of the ground.

In the case represented by fig. 157, which has been suggested by the structure of the Chalk Wolds of Lincolnshire, the outlier and inlier are caused by undulations parallel to the strike, but they are perhaps more often produced in nature by undulations across the strike, of the kind illustrated by fig. 81; the synclinals leading to the formation of outliers beyond the escarpment, and inliers occurring where the anticlinal folds happen to be crossed by some river-valley inside the main line of escarpment.

Among the older rocks which have been thrown into much sharper curves and contortions, outlying basins sometimes occur containing a great thickness of beds in their centre (see fig. 154), showing that a corresponding thickness must have been removed from the surrounding districts.

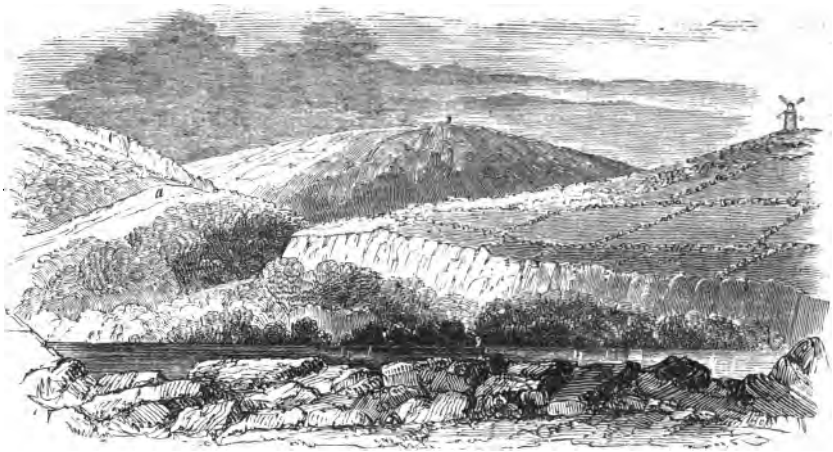


Fig. 158. View of Crich Hill, Derbyshire, from the West.

Flexures, however, are not the only conditions which give rise to the production of outliers and inliers. Faults, by causing an upthrow or downthrow of beds, may bring them into such positions that portions are afterwards isolated by erosion. Thus, if the beds in figs. 156 and 157 were traversed by a strike-fault along the line marked F F, instead of being bent into an anticlinal, an inlier might still be produced by erosion, though, in that case, its

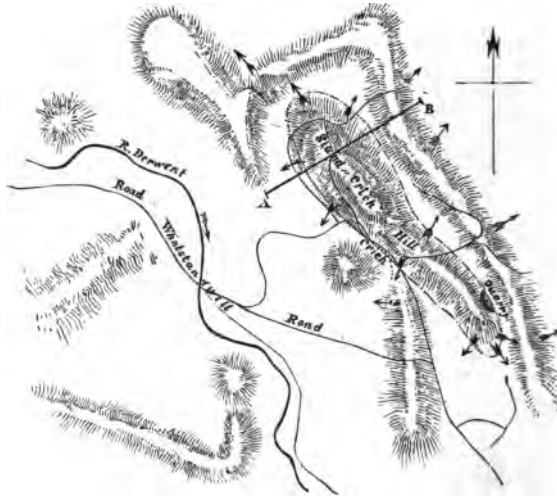


Fig. 159. Sketch map of the Crich Hill District, by H. Carr, C.E. The arrows indicate observed dips. Scale, 1 inch to a mile.

western boundary would be formed by the line of fault. An inlier so produced is represented at C M, fig. 109, p. 363. This would be called a faulted inlier; and an outlier, similarly separated by a fault from the main mass, is called a faulted outlier. In such cases the inlier is always on the upthrow side of a fault, and an outlier is always on the downthrow side.

Occasionally it happens that a piece of ground enclosed by two or more faults has been bodily lifted up through a

certain vertical distance, and the upper beds being subsequently removed by denudation, the lower beds are more or less exposed, and form an inlier. Crich Hill, near Matlock, in Derbyshire, is an excellent example of such a faulted inlier. The appearance and structure of this hill are illustrated by the four following figures.[1] Fig. 158 is a

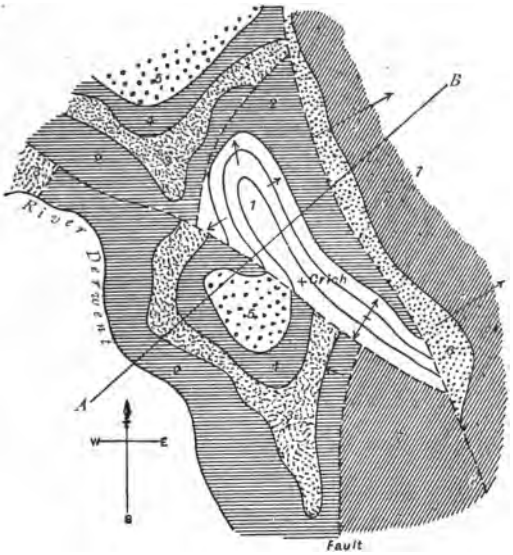


Fig. 160. Geological Map of the Crich Hill District.
Scale, 1 inch to a mile. Dips shown by arrows.
The broken lines are faults.
1 = Limestone. 2, 4, 7 = Shales. 3, 5, 6 = Grits and sandstones.

view of Crich Hill from the river Derwent, whence it appears as a dome-shaped eminence, encircled by precipitous escarpments of less elevation than the central hill, the height of which is about 800 feet above the sea, and is crowned by a tower called the *Stand*.

The dimensions of this central hill, and its position with

[1] Figs. 158 and 159 are taken from Mantell's "Medals of Creation."

regard to the surrounding escarpments, will be understood by reference to the sketch-map, fig. 159, which represents the physical geography of the district, while its geological structure is shown in fig. 160. A comparison of these two maps serves also to show the difference between an ordinary map or ground plan, and a geological map, on which the rock-structure of a district or country is delineated.

From fig. 160 it will be seen that Crich Hill itself consists of limestone, the beds of which are bent into an anticlinal curve, which becomes almost a periclinal at the north end of the hill. The surrounding escarpments are formed by the outcrop of several beds of hard grit and sandstone interstratified with softer shales, while it is along the course of the latter that the valleys of the district have been excavated. The dependence of physical features upon

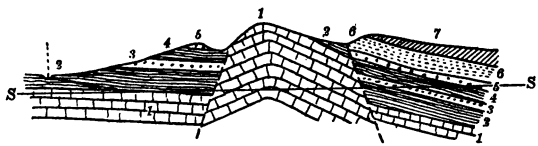


Fig. 161. Section through Crich Hill.

geological structure is here, therefore, excellently illustrated.

From the map (fig. 160) it is seen that the country is traversed by two main lines of fault, which, together with a cross fault on the north-west, completely cut off the Crich Hill area from the surrounding district. The triangular tract bounded by these faults has been pushed bodily upwards, till the upper surface of the limestone (1) was raised above the level of the sandstone (6), as shown in the section (fig. 161) along the line, A B. Furthermore, during the process of erosion and denudation by which the physical features of the country have been produced, the whole of the beds, 2, 3, 4, 5, 6, 7, have been removed from the surface of the limestone that forms Crich Hill, so that this satisfies the definition of an inlier, and becomes a measure of the amount of the denudation that has taken place.

Such a section as fig. 161 is also useful as showing the

close relation that often exists between bending and fracture. The force which produced the anticlinal uplift must have been continued until the strain of bending was relieved by actual fracture and displacement.

4. *Mountain Chains.*—Mountain ranges, as explained on p. 459, have been formed by successive uplifts, and in many cases there is no evidence that the range has ever been completely submerged since the first uplift took place; nay, if, as seems probable, successive uprisings are actually due to the restoration of hydrostatic equilibrium upon the lightening of the crust by the removal of material, then we may conclude that the process of denudation has been in continual operation ever since the first upheaval of the chain. We should consequently expect to find that a greater thickness of rock had been removed from the summits of mountain ranges than from any other parts of the earth's crust.

It can often be proved that the total amount of rock removed from the central axis of a mountain range is enormous. Captain Dutton has recently estimated the amount of rock removed from the Rocky Mountains of the Colorado region since their first upheaval, and believes it to have averaged 10,000 feet in thickness over an area of 13,000 to 15,000 square miles in extent. The Alps date from a still more recent period than the Rocky Mountains; but the compression to which the rocks composing them have been subjected seems to have been much greater, and therefore the total amount of vertical upheaval along their axis has probably been greater than in the case of the American range; but as their average height is about the same, the amount of denudation must have been greater in the case of the Alps. This inference is borne out by the facts, for the thickness of the sedimentary deposits affected by the upheaval of the Alps, and exposed by denudation, has been estimated at about 50,000 feet; and this thickness may be regarded as the amount of rock removed from the summits of the Alps since their first upheaval.

It is necessary to guard the student against supposing that the removal of 50,000 feet of rock from a mountain range means that the range must have been 50,000 feet high at some period of its history. It need never have

been much higher than it now is, because the two processes of upheaval and degradation have gone on together, and it was only in consequence of the repeated upheavals that so great a thickness of rock was removed. The process may be compared to the uprising of an iceberg out of the water, in proportion as the top is melted away by the sun, or to a piece of machinery, one part of which raises a block of wood or metal, while another part planes off the surface of the material as fast as it is brought within its reach.

Mountain ranges, therefore, differ from other hills as being mountains notwithstanding and in spite of the immense amount of detrition and denudation which has taken place over and around them.

General Conclusions.—From what has been said in this and preceding chapters the reader will be prepared to accept the statement that almost all the external features of the land, hills, glens, valleys, and plains have been produced by erosion. Their form is a sculptured form, carved out of the rocks by the operation of all those agencies which have been described in the earlier chapters of this work. These agents combine to form a great surface-carving machinery, and the disturbing forces which result in the upheaval of land are chiefly efficient in bringing the rock within the influence of the erosive agents, and are seldom productive of any direct effect upon the form of the ground.

Three distinct processes may generally be traced in the development of those physical features by which the surface of the land is diversified.

1. The block or mass of land out of which these features are subsequently carved is upheaved from beneath the sea.

2. Every part of this block as it reaches the sea-level suffers from the erosion of the waves, which prepare the surfaces of planation or marine denudation.

3. The inequalities of hill and vale are then carved out of these surfaces by the atmospheric and fluviatile agencies already described. The only exceptions to the rule that the form of the ground is due to detrition and erosion, are to be found in the alluvial flats and deltas of rivers, in

hills of blown sand, and in the cones of active volcanoes on which the rain has not yet produced any appreciable effect.

It must be remembered, however, that in the case of mountain chains, though the forms of the peaks and valleys are the work of erosive agencies, yet the existence of the range itself is due to the force which has caused its elevation. Fig. 149 has been given as a simplified section across such a range, and though, of course, their structure is in reality much more complicated, still the diagram will serve to explain the process of their formation and to show what is meant by *hills of upheaval* compared with *hills of circum-detrition*, which have been amply illustrated by the preceding figs. 151, 152, 154. Detrition may have been equally active in both cases, and indeed the amount of material removed may have been greater in the former than in the latter case: but the comparative elevation of the ground is in the latter chiefly caused by the removal of the surrounding parts, while in the former the hills would have been more lofty if the detritive agents had been less active.

To sum up, therefore, the principal features of the earth's surface may be thus classified according to their mode of origin.

Valleys are of one kind only; they have all been formed by the erosive action of rain, springs, and rivers.

Plains are of two kinds: 1, plains of formation; 2, plains of denudation.

Plains of formation are such as are formed by the undisturbed extension of beds which retain the original horizontality of deposition. River deltas, and alluvial flats, fens, marshes, and silted-up lakes are instances of such plains. In this class may also be included the slightly inclined or undulating surfaces sometimes produced by the elevation of a shallow sea-bottom which special local causes have exempted from the action of marine erosion; such are the Pampas of South America, the Tundras of Siberia, large tracts in Russia and Poland, and perhaps also the great Sahara Desert in North Africa.

Plains of denudation are those which have been formed by marine erosion across the edges and outcrops of strata

without reference to their inclination, flexures, or fractures. They are surfaces of planation formed by the march of the sea across the country. The limestone plains of central Ireland may be cited as an instance, the country bordering the rivers Rhine and Moselle is another, and the plains of Cheshire is a third. When elevated to a considerable height above the sea-level, they form what are known as *table-lands*.

Hills are of three kinds: 1, hills of accumulation; 2, hills of circum-detrition; 3, hills of upheaval.

Hills of accumulation are such as have been formed by the piling-up of materials upon the surface of the ground. Volcanoes are the most important instances; these are conical piles formed by the ejection of ashes and lava streams (see fig. 1). Sand hills heaped up by the action of wind on drifting sand come under the same category.

Hills of circum-detrition are such as have been left by the removal of the surrounding rocks, or are isolated by valleys of erosion. They have been illustrated by figs. 151, 154.

Hills of upheaval are those formed by the elevation of a central axis faster than it can be worn down by detritive agencies, see fig. 149.

I

I

II

PROFILE OF MONT DORE.

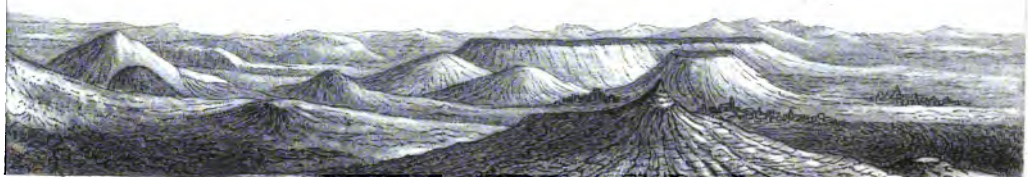
Plan of the Crater

II

III

VIEW OF THE CHAIN OF PUYS; MONT DOME IN THE DISTANCE

III



VIEW OF THE ENVIRONS OF CLERMONT, FROM THE PUY GIROU.

E. Weller Sculp.

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